THE DESIGN, FABRICATION AND EVALUATION OF THE AURAL ANGLE OF ATTACK/STALL WARNING SYSTEM

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THESIS

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by

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ABSTRACT

Maximum performance and stall avoidance can only be realized in high-performance aircraft if the pilot is fully aware of angle of attack. Because present methods of providing this information have proven to be inadequate, an alternative method has been proposed. This paper describes the Aural Angle of Attack/Stall Warning System, an electronic device which produces a coded aural display meeting the requirements of 1) providing angle of attack information in the large angle of attack region, 2) providing positive warning of approach to and passage through stall angle of attack and 3) accomplishing these without distracting from the primary visual task. Evaluations were conducted utilizing a simulated tail-chase tracking task, a full-scale air combat manoeuvering simulation and actual aircraft testing. Results indicated that 1) there was marked improvement in pilot performance in the air combat manoeuvering environment with the addition of an aural system, 2) the electronic package could operate efficiently in an actual aircraft and 3) the aural system has a definite utility in the take-off and landing phases of flight.

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A	Operational amplifier gain
AAA/SWS	Aural Angle of Attack/Stall Warning System
ACM	Air combat manoeuvering
g	Radial acceleration on a pilot in turning-flight normalized with respect to the force of gravity
g_{ij}	Inverse hybrid parameter
I	Current flow, amperes
I_{ij}	Current flowing into pin i in component j, amperes
Hz	Hertz
in.	Inches
lb	Pounds force
op-amp	Operational amplifier
R_g	External op-amp resistance between non-inverting terminal and ground, ohms
R_i	External op-amp input resistor i, ohms
R_o	External op-amp feedback resistor, ohms
sec(s)	Second(s)
T	Fixed period of saw-tooth waveform, seconds
V	Component voltage, volts
V_α	Angle of attack transducer output
V_{ci}	Output voltage from logic device i, volts
V_{c23}	Logic device output voltage used for on-off switching, volts
V_{fm}	Voltage used for frequency modulation, volts
V_{pwm}	Voltage used for pulse-width modulation, volts
V_{ZL}	Zero-limited voltage, volts

V_{ij}	Input voltage i to op-amp j, volts
V_{2j}	Output voltage from op-amp j, volts
$V_{ⓘj}$	Input voltage j to logic device i, volts
$V_{2ⓘ}$	Output voltage from logic device i, volts
VCO	Voltage controlled oscillator
W	Tone on-time, seconds
Z_n	Op-amp internal input impedance, ohms
Z_o	Op-amp internal output impedance, ohms
α	Aircraft angle of attack, degrees
α_2	Beginning of region of useful angles of attack in large angle of attack region, degrees
α_3	End of region of useful angles of attack in large angle of attack region, degrees
α_{st}	Stall angle of attack, degrees
α_{th}	Threshold angle of attack, degrees
ζ	Coefficient of damping
λ	Inverse of time constant, seconds^{-1}
$\dot{\phi}$	Aircraft roll rate, radians/second
$\dot{\theta}$	Aircraft pitch rate, radians/second
ω	Aircraft longitudinal natural frequency of oscillation, radians/second
Ω	Ohms

ACKNOWLEDGEMENTS

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I. INTRODUCTION

Stall/spin accidents in high-performance aircraft continue to increase because these aircraft, designed as they are for maximum performance at high speed and low angle of attack, exhibit extremely poor handling characteristics at large angles of attack. These characteristics result from the adverse effects which long-pointed noses, high fuselage loading, thin wings with sharp leading edges and other high-speed design criteria have on stability derivatives at low speed. They also contribute to violent departures with little warning in the region of large angle of attack.

Nevertheless, pilots of such aircraft sometimes choose to fly in this region and, when they do, it is usually for one of two reasons: they are either seeking an optimum or maximum performance angle of attack or attempting to decelerate rapidly. In either condition their objective is to fly at the particular angle of attack which gives them the desired performance and in neither case do they wish to exceed stall angle of attack.

Such aircraft are presently equipped with devices which measure and display the aircraft angle of attack. The primary means of providing this information to the pilot is via visual display, which is adequate for all regimes of flight except those in which there are high visual requirements outside of the cockpit, in which case the pilot's ability to acquire

stall information visually is seriously degraded. Flight in the large angle of attack region is accompanied by external visual tasks of this type, eg. landing and air combat manoeuvering (ACM). Since the acquisition time for the visual display necessarily reduces the attention given the primary external task, the pilot excludes the angle of attack indicator from his scan and reverts to a less efficient method of acquiring the information, i.e. he monitors the behavior of the aircraft itself. Typically referred to as "seat of the pants" flying, this method depends upon visual, tactile and kinesthetic cues provided by aircraft motion, which are indicative of the angle of attack being either sought or avoided. In the former case, cues such as airframe buffet, control stick position and forces and "g" loading are used while in the latter, unstable behavior such as nose wandering and decreased pitch damping may be the indicators. In both cases, the ability to perceive any or all of these cues is adversely affected by other behavior and by rapid changes in the environment in which flight is taking place, eg. airframe buffet, lateral accelerations and airspeed and altitude changes.

However, the ability of the pilot to locate and fly at specific angles of attack under these conditions must be questioned. While he may be able to fly close to the desired angle of attack or region, it is unlikely that the difference between his actual angle of attack and that sought would be consistently small. Failure to achieve this objective

results in a loss of performance and, depending upon the conditions, this degradation can manifest itself in other more serious losses. In ACM for instance, failure could result in loss of advantage or inability to generate angle-off. In weapons delivery it could mean excessive time spent at roll-in or less than maximum performance during pull-off. Add the elements of a hostile environment and the ultimate loss could be the aircraft.

In essence, the success with which a pilot uses this "seat of the pants" method is largely dependent upon his experience and ability and the type of aircraft he is flying. Earlier aircraft with mild instabilities, slowly progressing stalls and docile departures provided large margins for error; however in present aircraft the margin has been drastically reduced and accident statistics point out that the seats of some pilots' pants are less sensitive than others.

Since all aircraft are presently equipped with some type of angle of attack sensor to warn the pilot of approach to stall, the question of why stalls are not being avoided must also be considered. Since the majority of these devices fail to present their information in an effective manner, the answer seems to be that their display can be and is being ignored or misunderstood by many pilots.

Therefore, it can be concluded that maximum performance and stall avoidance can be realized only if the pilot is fully aware of aircraft angle of attack. Because present methods of providing this information have proved to be

inadequate, an alternative method has been proposed. This paper describes the design and evaluation of the Aural Angle of Attack/Stall Warning System (AAA/SWS), a coded aural display which meets the requirements of 1) providing angle of attack information in the large angle of attack region, 2) providing positive warning of approach to and passage through stall angle of attack and 3) accomplishing this without distracting from the primary exterior visual task.

II. SYNTHESIS OF THE AAA/SWS

A. INTRODUCTION

An aural display of the angle of attack information was selected as the alternative to visual display for several reasons:

1. Reference (1) suggested that an aural display be employed whenever a critical visual task requires continuous monitoring and at the same time additional information needs to be imparted. Moreover, auditory display has a major advantage in that the pilot need not physically face the source of the signal to act upon it. Finally, the human auditory perception system is remarkably capable of discriminating among sounds and is ideally suited for sorting usable signals from noise.

2. Studies of simple human response indicated that an aural stimulus elicits a response which may be 10 to 30 msec faster than the response to a visual stimulus.[(2),(3)]

3. A study of aural compensatory tracking tasks conducted by Vinje and Pitkin[(4)] demonstrated that control of the task was equally effective using either visual or aural displays. In addition, Vinje has more recently reported[(5)] that results from research involving control of a V/STOL aircraft in a hover task indicated that aural presentation of information vitally important to the pilot markedly improved his overall performance by enabling him to eliminate the normally used visual indicator from his scan and thus spend more time on the remaining visual task.

4. Other displays which appealed to different sensory channels, e.g. tactile display, were considered but difficulties in the implementation of the proposed system and the anticipated inability of the system to satisfy objectives previously listed resulted in their being discarded.

B. DISPLAY FORMAT

Once it had been determined that an aural display would be utilized, the format employed to accomplish the objectives had to be designed. As a first step in this process, the disadvantages and limitations of present methods which attempt to do the same things were identified and are listed in Table I. Examination of these deficiencies revealed that all of those systems investigated had presentations which suffered from at least one of the following maladies in the large angle of attack region:

1. Inability of the pilot to determine location and direction and rate of movement of angle of attack.

2. Difficulty in receiving and perceiving the angle of attack information in the display.

3. Not positively identifying approach to stall and precisely locating stall angle of attack.

Consequently, to be recognized as an improvement the AAA/SWS had to overcome these deficiencies; in addition, it was stipulated that it had to be possible to positively identify other angles of attack besides stall. These factors collectively represent the objectives which were utilized in the design of the format for the AAA/SWS.

A plain-language voice display was initially considered but was rejected due to excessive costs and anticipated difficulties in meeting format objectives. Instead, an easily recognized coded aural display was chosen which employs a periodically displayed tone which is simultaneously frequency and pulse-width modulated as a function of aircraft angle of attack. Initiation of the AAA/SWS display occurs when aircraft angle of attack (α) exceeds a predetermined threshold value (α_{th}) and presentation is continous whenever $\alpha \geq \alpha_{th}$. A detailed description of the format follows:

1. Frequency Modulation

To provide the pilot with direction and rate of movement information the frequency of the tone is modulated from a base value (f_o) of 500 Hz at α_{th} to 1500 Hz at stall angle of attack (α_{st}). (See Fig. 1a). This range of frequencies was chosen in view of several considerations:

a. Sensitivity

Described as the ability of the auditory channel to make effective use of the minimal amount of vibratory energy,[6] sensitivity has been studied by several researchers and as reported by Wegel,[7] the threshold of sensitivity is greatest in the region between 400 and 5000 Hz (see Fig. 2). In addition Fletcher and Munson[8] showed that the least variation of intensity with frequency is present in the range between 500 and 4000 Hz (see Fig. 3). These suggested that once a volume level had been selected

no further adjustments would be needed throughout the frequency modulation schedule.

b. Pitch Discrimination

Research conducted by Shower and Biddulph[9] revealed that pitch discrimination, the ability to appreciably sense the difference between two tones, is at a maximum, requiring only 3Hz difference to be perceptable, and that this discrimination is constant across the frequency range 100 to 2000 Hz. (See Fig. 4). This promised a uniform discrimination of changes in frequency when the modulation was linear with angle of attack.

c. Pitch vs Intensity

As reported in ref. 1, perception of pitch is affected by the intensity of the tone at both low and high frequencies. With an increase in intensity, low tones (below 500 Hz) appear lower and high tones (above about 4000 Hz) appear higher. In the middle frequencies, where the ear is most acute, intensity changes have little, if any, effect on pitch. Tones located between 500 and 4000 Hz maintain almost constant pitch even when varied over wide intervals of intensity.

2. Frequency Step

To positively identify α_{st}, the frequency of the tone is abruptly stepped by 700 Hz at α_{st} from 1500 to 2200 Hz.

3. Pulse-Width Modulation

To provide information as to relative position with respect to α_{th} and α_{st} and to positively identify two other angles

of attack of interest between α_{th} and α_{st}, the ratio of tone on-time (W) to a fixed time period (T) is varied in a specified manner as a function of angle of attack, i.e. the tone is pulse-width modulated. (See Fig. 1b). The two angles of attack of interest (α_2 and α_3, where $\alpha_2 < \alpha_3$) are identified and the pulse-width modulation scheduled as follows:

a. α_{th} to α_2

Between α_{th} and α_2 the ratio W/T is 1.0, i.e. the tone is presented continuously; consequently changes in angle of attack are indicated by frequency modulation only in this region. The difference between α_{th} and α_2 is usually chosen to be small as this is primarily an introductory region to advise of the approach of the following region of interest.

b. α_2 to α_3

Between α_2 and α_3 the ratio W/T is varied linearly from 0.1 to 1.0 as a function of angle of attack; thus changes are reflected in both frequency and pulse-width modulation in this region. The angles of attack α_2 and α_3 are chosen such that all useful angles of attack in the large angle of attack region are contained between them. In addition to precisely locating α_2 and α_3, studies conducted in conjunction with this research showed that subjects were able to locate specific W/T ratios to within a high degree of accuracy with the region defined in this manner. In this way other angles of attack associated with particular W/T ratios can be located.

c. Above α_3

Above α_3 the ratio W/T is again set to 1.0. Since $\alpha_3 < \alpha_{st}$ and all useful angles of attack are contained between α_1 and α_3 , the region above α_3 is one in which continous flight is neither desirable nor advisable; consequently, the continous tonal presentation serves as a warning of either approach to stall or excursion from a desirable region of flight.

The final decision which had to be made with regard to pulse-width modulation was the selection of a specific fixed period. A choice of T = 0.3 secs was made as a compromise value due to the following conditions:

a. Loudness vs Tonal Duration

Duration affects loudness. Maximum loudness is attained at approximately 0.5 secs; beyond this interval there may be a slight decline in loudness as the ear adapts to the sound. For tones of very short duration the loss of loudness is pronounced. As reported by Munson,(10) this critical duration is about 0.2 secs, although it is somewhat dependent on frequency - low-frequency tones lose more loudness than do higher-frequency tones of comparable duration. To maintain equal loudness for tones shorter than the critical duration, the intensity required is inversely proportional to the duration.

b. Pitch Perception vs Tonal Duration

Results of research conducted by Turnbull(11) revealed that when duration of the tone is short the pitch

is affected. Pitch is indistinguishable for durations below 0.01 secs, ie. a tone will appear as a click. Above a tone duration of 0.01 secs the click gradually begins to take on pitch qualities but the pitch will normally appear lower than that of another tone of the same frequency but longer duration. An increase of tone duration up to 0.1 sec will result in improved pitch qualities. Figure 5 illustrates this phenomenon and indicates the number of cycles required for a short duration tone to take on pitch.

c. Ability to Identify W/T Ratios

Studies carried out in conjunction with this research indicated that the ability to identify specific W/T ratios diminished significantly when the fixed period was greater than 0.3 secs.

C. ELECTRONICS PACKAGE

With the format of the AAA/SWS determined, the actual device to produce the coded aural display was designed and fabricated with the following being used as guidelines. The device fabricated had to be:

1. able to produce the required display given only aircraft angle of attack.

2. inexpensive in terms of fabrication and installation costs, volume required in and weight added to the aircraft and opower required for operation.

3. reliable under all operating conditions.

By making use of printed circuit technology and recent advances in the field of solid-state electronics, a small

($4 \times 6 \times 1$ in) lightweight, (≤ 1 lb) low cost, ($< \$100.00$) AAA/SWS electronics package was designed and fabricated. Specifications and component make-up as well as a detailed analysis of its operation are contained in appendix A. A brief general description of methods used in this device to satisfy the requirement of producing the specified format, given only aircraft angle of attack, follows:

1. Make-up of the Device

a. Input Section

This section receives the output of the aircraft angle of attack transducer, conditions it as required and outputs a properly scaled d.c. voltage proportional to aircraft angle of attack (V_α).

b. Angle of Attack Detection Section

This section receives V_α and in a preconditioning subsection limits the signal to zero when the aircraft angle of attack is less than and to a positive-going d.c. voltage (V_{ZL}) when it is greater than α_{th}. This signal is monitored in separate discrete logic devices to detect α_{th}, α_2 and α_4 and indicate them with V_{c1}, V_{c2} and V_{c4} respectively. In addition V_{ZL} is compared with an internally generated periodic ramp function of period 0.3 secs with upper and lower limits which correspond to α_3 and α_2, respectively ($V\alpha_3$ and $V\alpha_2$), to produce the signal V_{c23} utilized for on-off switching.

c. Signal Preparation Section

The separate signals are combined with other internally generated signals in this section to produce two

output signals V_{fm} and V_{pwm} which are used for frequency and pulse-width modulation respectively.

d. Output Section

This final section produces the required AAA/SWS formated tone which is routed to the pilot. It utilizes <u>A</u> voltage controlled oscillator (VCO) which is regulated by V_{fm} and a switching device controlled by V_{pwm}

2. <u>Block Diagram of the Device</u>

A block diagram of the AAA/SWS electronics package with graphical representations of the various section input/output relationships is shown in figure 6.

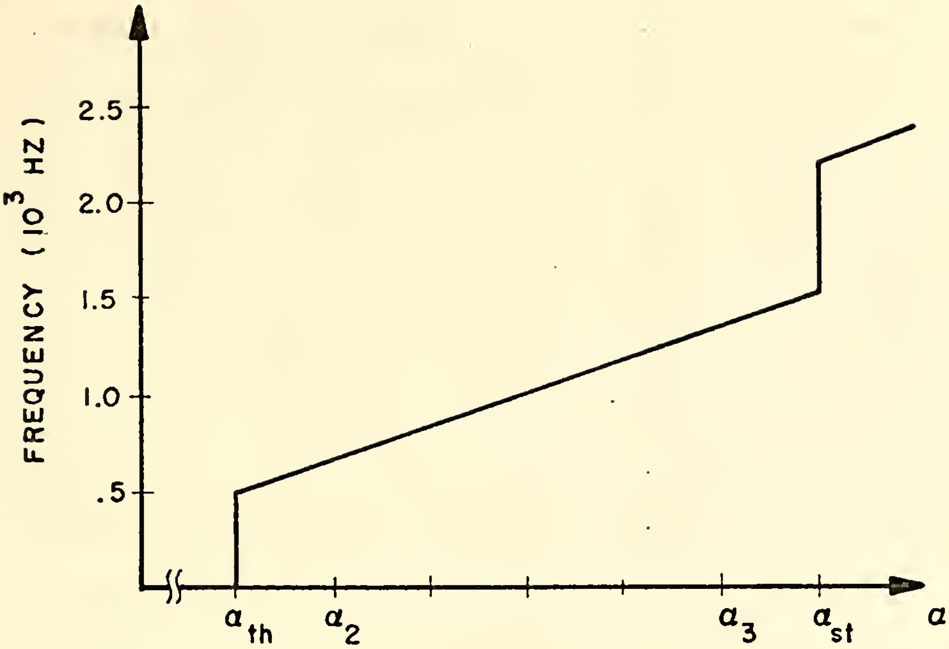


Figure 1a. Frequency Modulation Schedule

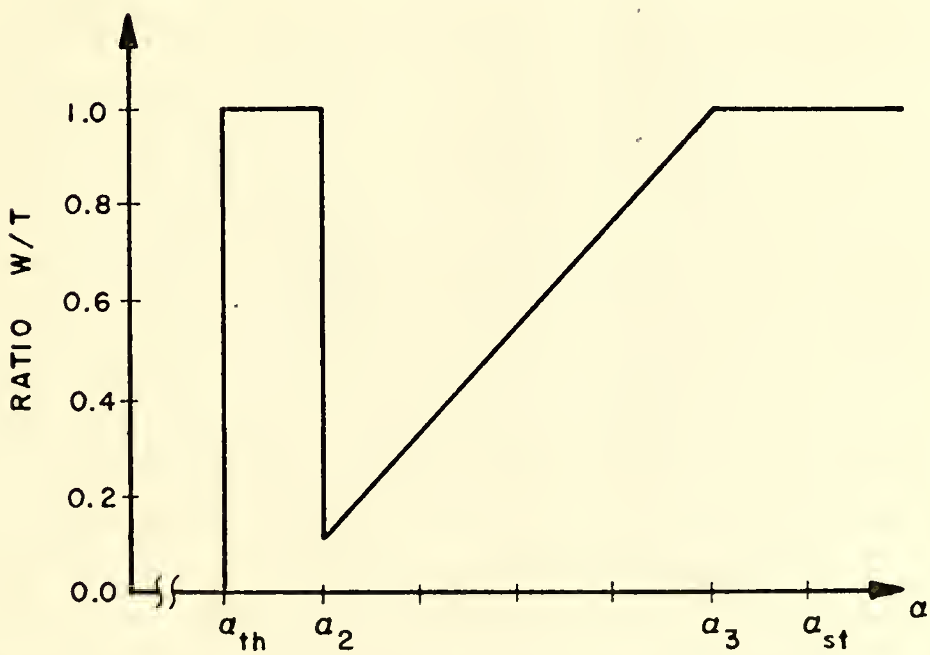


Figure 1b. Pulse-Width Modulation Schedule

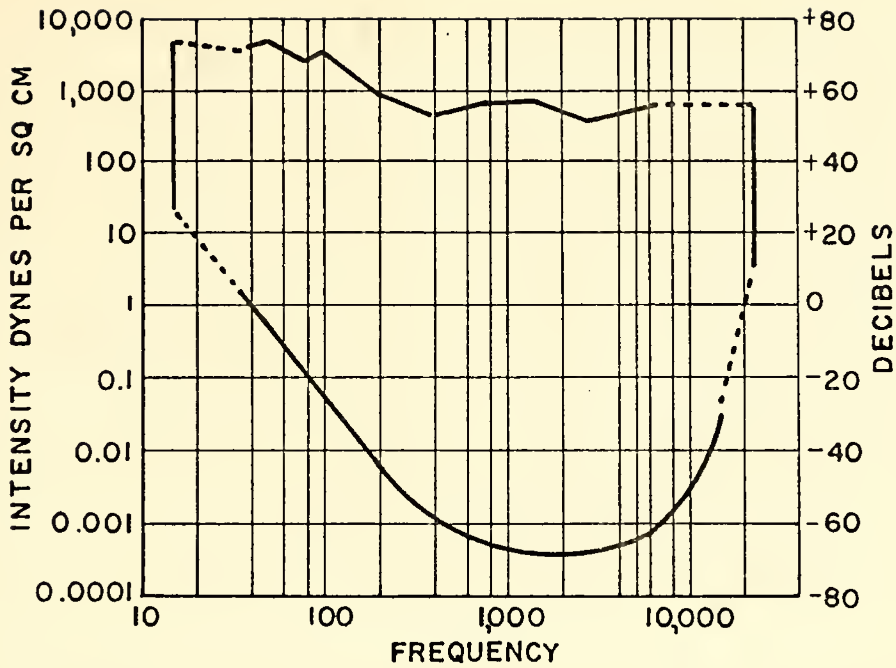


Figure 2. The Auditory Area. The lower boundary is the curve of threshold sensitivity, and the upper is the limit at which pain, pressure, and other sensations supervene.

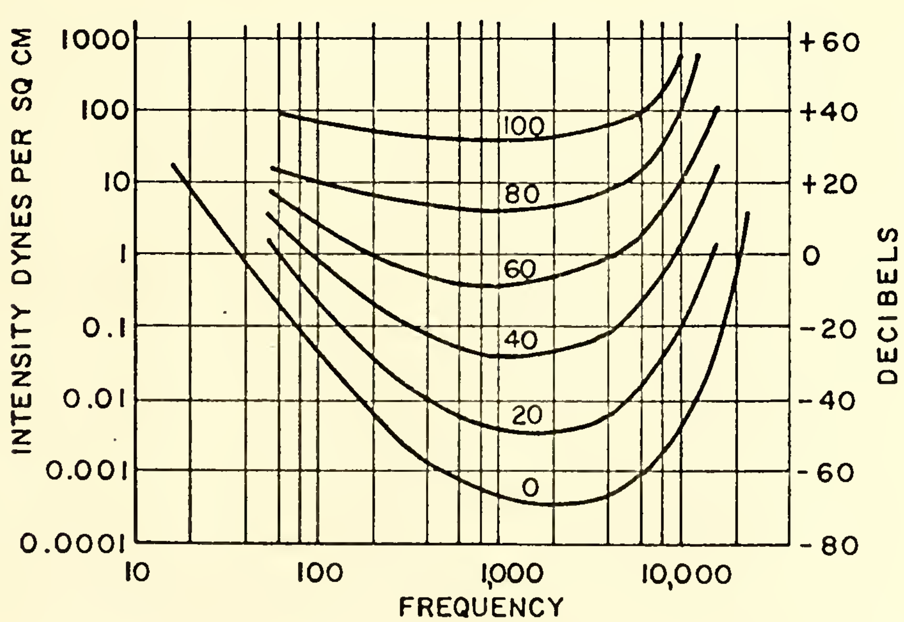


Figure 3. Equal-Loudness Contours. Each curve represents the intensity required to produce a tone judges equal in loudness to a 1000 Hz tone whose level above threshold is indicated on the curve.

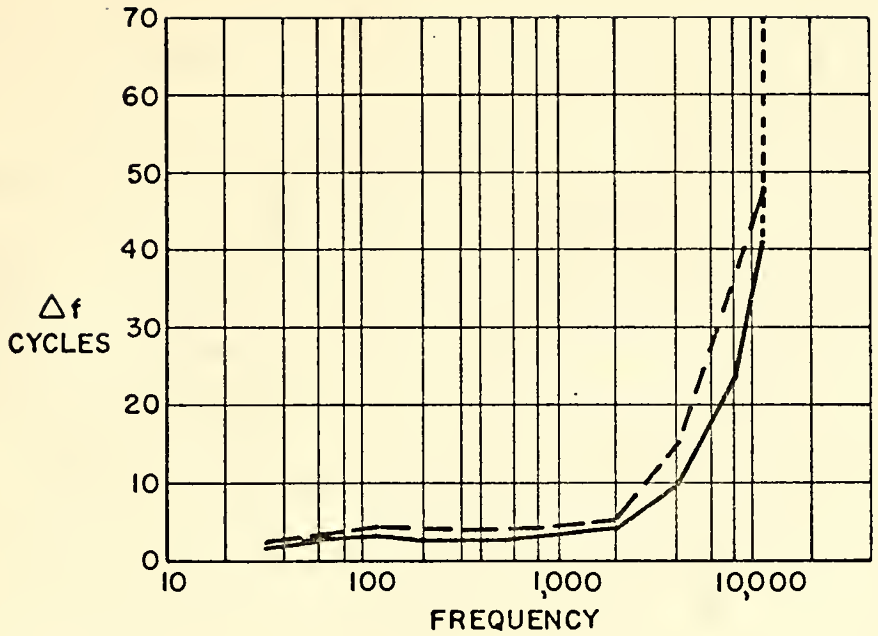


Figure 4. Pitch Discrimination. Shown are the changes in cycles (Δ f) that are barely discernable, when the tones are warbled at a rate of 2 per second. The solid curve shows results for tones 40 db above threshold, and the dashed for 15 db above threshold.

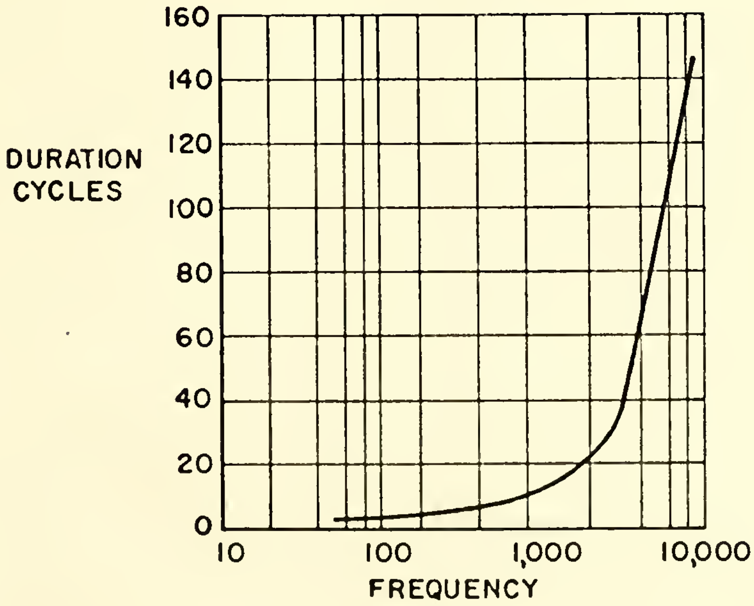


Figure 5. Pitch in Relation to Tonal Duration. The duration is measured as the number of cycles in the pulse of tone that is judged just long enough for the pitch to be recognizable or that permits pitch discrimination.

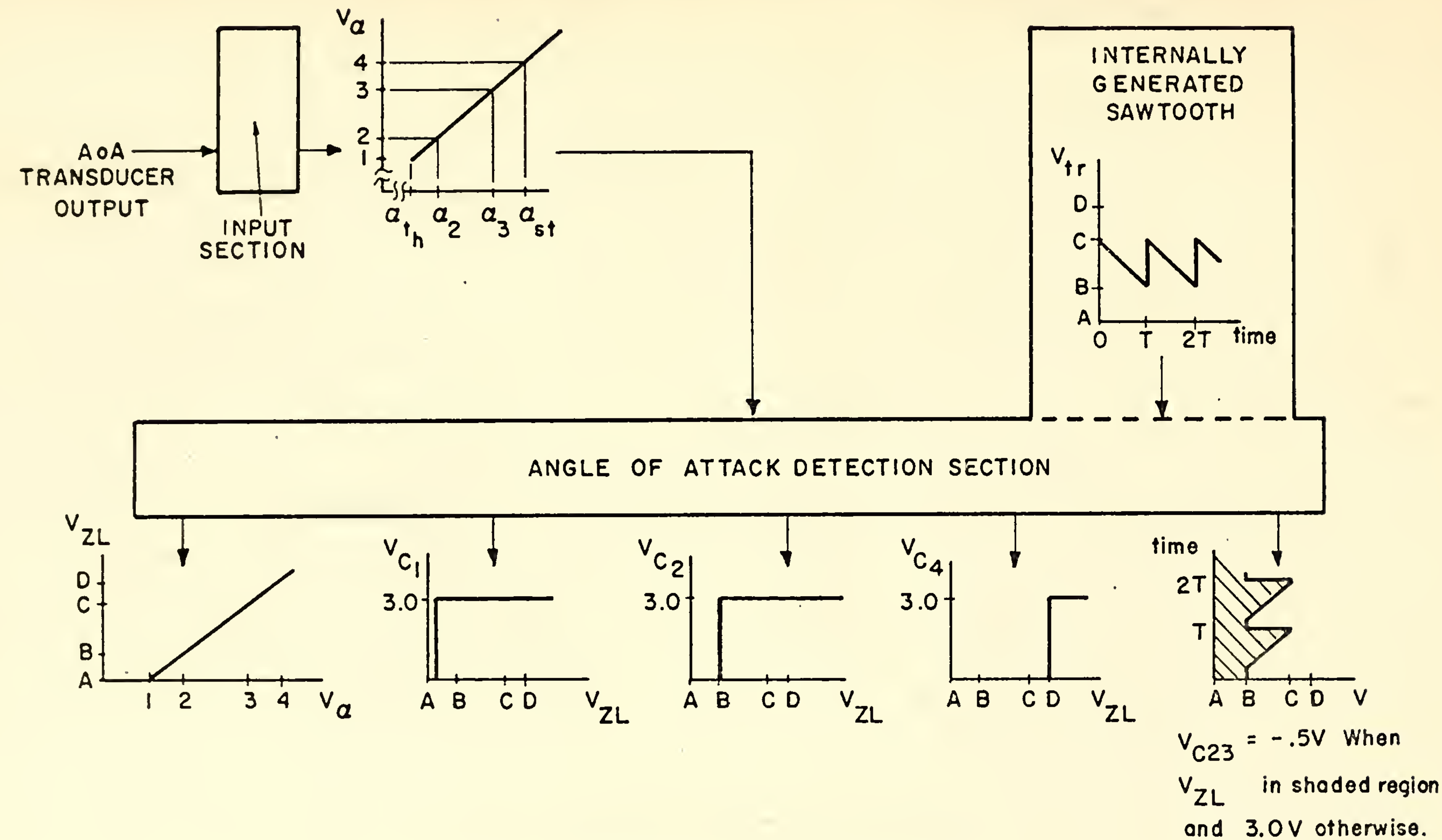


Figure 6a. Input-Output Relationships for AAA/SWS

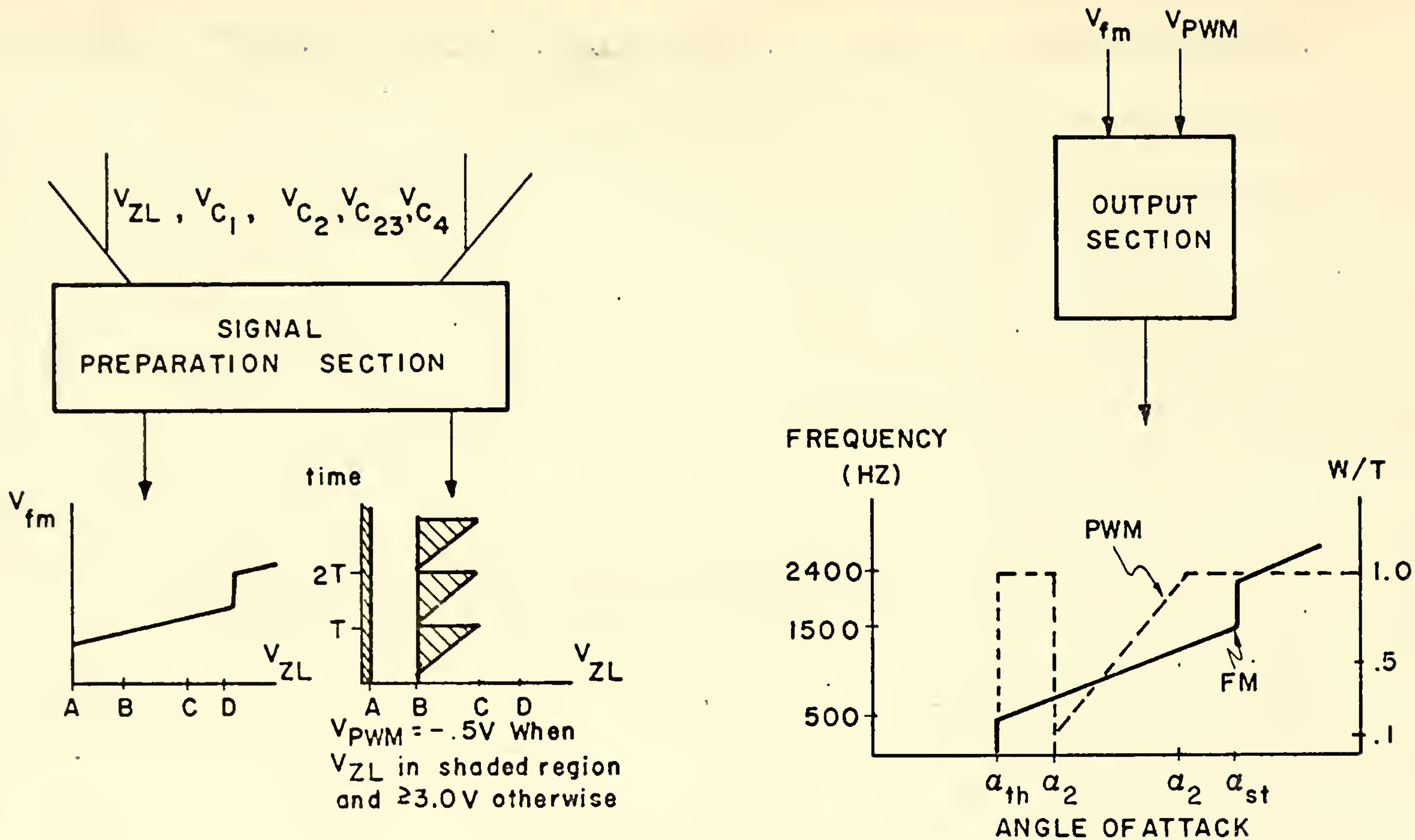


Figure 6b. Input-Output Relationships for AAA/SWS

Display Type	Method of AOA Acquisition	Method of Stall Warning	Disadvantages
Aircraft Characteristics	Aircraft Behavior and Motion, Forces and Accelerations	Buffett, Unstable Tendencies	1. Not uniformly perceived by all pilots. 2. Dependent upon many parameters which change rapidly in dynamic environment. 3. Instabilities build-up rapidly with little or no forewarning. 4. Small changes in AOA difficult to distinguish. 5. Buffet begins early in region due to sharp leading edges, and build-up not always proportional to AOA.
Visual	Gauges, dials on instrument panel or HUD. Indexer lights.	Flashing lights or position of indicating mechanism on gauge or dial.	1. Fixed location of display not always in field of view of pilot. 2. Focus from infinity to display distance if primary visual task is outside cockpit. 3. Fixation on display necessary for AOA acquisition. 4. Sampling required in dynamic environment therefore rate information limited. 5. Indexer lights are single AOA limited in that they identify a single AOA precisely and information as to whether AOA is above or below it but not how far.

Display Type	Method of AOA Acquisition	Method of Stall Warning	Disadvantages
Aural	Formated tones (Air Force F-4 System, British System)	Horns, Buzzers and others	1. Both British and Air Force Systems are single AOA limited. 2. Air Force System has been reported to be confusing in format and annoying. 3. Neither British or Air Force Systems provide stall AOA warning. 4. Buzzers, etc. frequently disabled by pilots because of annoying presentation, and of no value for other AOA identification.
Others		Mechanical Shakers (control stick and rudder pedal)	1. Often masked by airframe buffet. 2. Does not identify stall AOA since it comes on below stall. 3. No AOA information other than when it comes on.

Table I. Disadvantages and Limitations of Present Method of AOA Display.

III. TESTING OF THE AAA/SWS

A. INTRODUCTION

The overall objective of the testing program was to measure the effect of the AAA/SWS on pilot performance and confidence level, i.e. his assurance in his knowlege of location in the large angle of attack region. The data from which measurements of its effect were extracted varied from purely quantitative, eg. RMS difference between performance parameters of two aircraft engaged in ACM, to strictly qualitative, eg. pilot comments on the benefit derived by having the AAA/SWS display in the landing pattern. In addition, the environments in which the testing was perfomed included a two-axis compensatory tracking task simulating an aircraft tail-chase situation, a full-scale simulation of a current Navy variable-sweep fighter aircraft engaged in ACM and flights in actual aircraft. A brief description of each of the phases of the testing program follows.

B. LABORATORY TESTING

Meaningful quantitative data which were true measures of pilot performance could only be obtained in a controlled environment such as that offered by the Computer Laboratory located at the Naval Postgraduate School in Monterey, California. For this portion of the AAA/SWS evaluation a two-axis compensatory tracking task (see Fig. 7a) was devised which simulated a tail-chase tracking problem in ACM.

Utilizing a situation display like that shown in Fig. 7b, the pilot flew the attacker aircraft with an isometric side-arm controller so as to minimize the target RMS radial error for the length of the run. As shown in Fig. 7c, control of the attacker pitch rate was through a variable stability second-order system and of the roll rate through a variable time constant first-order system. Variation of the respective system parameters with angle of attack and their relationships to α_{th}, α_2, α_3 and α_4 are shown in Fig. 8. The forcing functions of target pitch and roll rates were a combination of a constant bias, a ramp function and a sum of four sine waves. Table II lists the equations utilized and the frequencies and amplitudes which were employed to produce the four target tracks used in testing. Since the target aircraft's rates were selected to force the attacker frequently to fly in the large angle of attack region, and since the target had a performance advantage in that region, the attacker pilot had to monitor angle of attack to prevent stall and departure.

The attacker aircraft's angle of attack was displayed in one of three ways during each test run:- aircraft behavior, or AAA/SWS, or convential visual display, i.e. a panel-mounted gage with a rotating pointer. The sampling time of the visual indicator was simulated by requiring that the pilot call up the display from a hidden position with a push button when it was desired. The display appeared at a random location on bottom of the situation indicator (see Fig. 7b),

remained for 0.6 secs and then disappeared from view until called up again. Sufficient warm-up flights were performed to ensure pilot familiarity with all the types of display and the tracking tasks.

Measurements were taken during each run by identifying time periods in each target track, called alpha windows, in which the target's performance was such that the attacker had a high probability of departing if he attempted to track the target precisely. The number of successful transits of each window, the RMS difference between target and attacker pitch rates, known as rate error, and the time of penetration into an alpha window in which a departure was experienced were the primary performance data recorded. In addition, pilots were given the opportunity to break-off an attack without penalty if they correctly determined that they could no longer track the target without departing. Since this also required an accurate knowledge of angle of attack it was considered as a possible data point and was recorded. A total of six (6) pilots of varying operational flight experience were employed in the testing. Each pilot tested three (3) times every possible combination of display types (3) and target tracks (4), for a total of 216 runs.

C. TESTING IN THE ACM SIMULATION

Further laboratory-type testing was carried out in a more realistic ACM environment in the Differential Manoeuvering Simulator (DMS) located at the National Aeronautics and Space Administration Langley Research Center, Hampton,

Virginia. The experimental design was similar to that described for the tail-chase task in that an attacker aircraft with instabilities in the large angle of attack region was required to maintain a prescribed tracking position on a target aircraft of similar but superior performance capabilities. Unlike the previous testing however, the aircraft employed were full-scale simulations of a current Navy high-performance variable-sweep fighter aircraft and the environment provided by the DMS was such that the tracking task involved control of an aircraft with six degrees of freedom in a visual task with 360° field of view. One of eight (8) preprogrammed target tracks of varying difficulty, i.e. the number of opportunities for the attacker to depart was presented to the attacker on each test run.

Since the target aircraft again had a performance advantage in the large angle of attack region, accurate knowledge of angle of attack was essential for the attacker pilot to achieve maximum performance from his aircraft during those periods when the target could no longer be tracked and thus maintain his advantage and avoid departure. Angle of attack information was displayed in one of two ways on each run - either conventional visual gage and indexer lights or AAA/SWS where α_{th}, α_2, α_3 and α_{st} were located with respect to the following aircraft phenomena:

1. α_{th} - Stall of the outer wing panels and beginning of the region where roll control had to be progressively transferred from ailerons to rudders.

2. α_2 - Slight roll instability (wing rock).

3. α_3 - Maximum turn rate, roll control transferred to rudders - angle of attack above which flight not advisable.

4. α_{st} - Beginning of uncontrollable directional divergence.

Measurements of RMS distances and angular position of the attacker aircraft with respect to the target were recorded on each run with the purpose of determining the ability of the pilot to remain within a prescribed area aft of the target. The pilot indicated his confidence in his position within this region and that he was tracking smoothly enough for weapons delivery by depressing the guns trigger. Data were taken which indicated the percentage of total run time the attacker remained in the designated area and the pilot was tracking, the total run time, the ability of the pilot to identify specific angles of attack and the number of excursions of attacker angle of attack above stall on each run.

D. AIRCRAFT TESTING

Qualitative evaluations of the AAA/SWS electronics package, its susceptibility to ambient noise effects on display reception and its utility in the take-off and landing phases of flight were determined in actual aircraft testing. In the final analysis, the ability of the AAA/SWS to function in the various environments such as those offered by ACM and weapons delivery, with noisy input signals from the aircraft angle of attack transducer and with less than ideal power supply, had to be evaluated. In addition, investigations into the capability of the pilot tc receive the AAA/SWS display in the presence of

ambient cockpit noise and perceive the information contained in its coded signal with other aural inputs interfering, and the desirability of having the AAA/SWS in take-off and landing, were warranted. Testing was performed with the AAA/SWS electronics package installed in a fully acrobatic light commercial aircraft capable of +7 g. Flight tests which consisted of acrobatic manoeuvering similar to that required in ACM and take-off and landing practice with two-way voice communications present were conducted by three (3) pilots from the Aero-Medical Branch of Service Test Division of the Naval Air Test Center, Patuxent River, Maryland. Pilot comments comprised the bulk of the data taken.

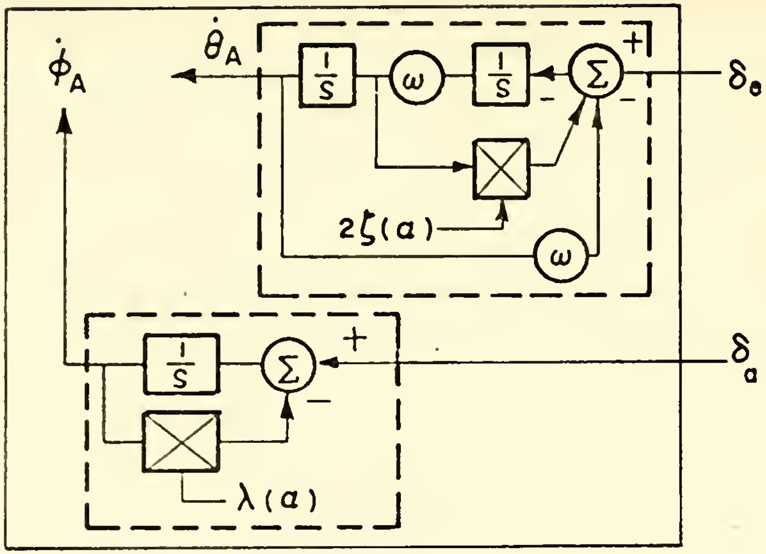


Figure 7c. Attacker Transfer Functions

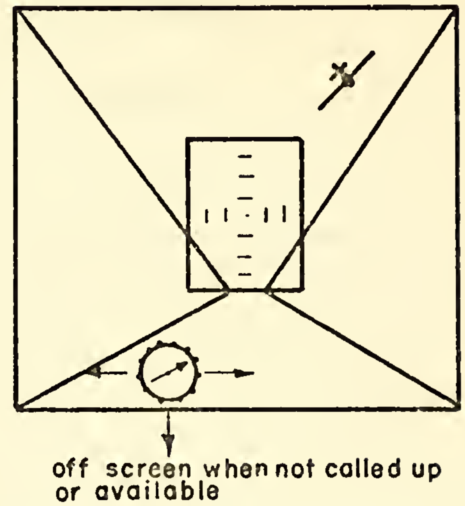


Figure 7b. Situation Display

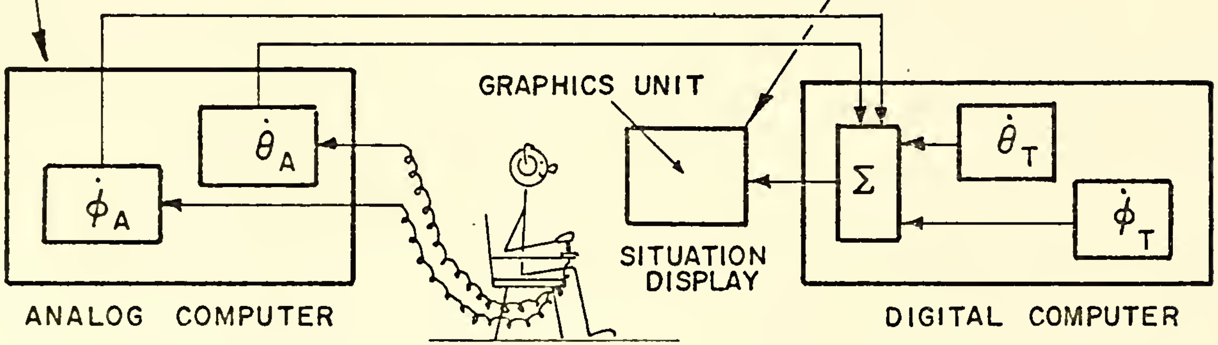


Figure 7a. Block Diagram of Two-axis Comdensatory Tracking Task

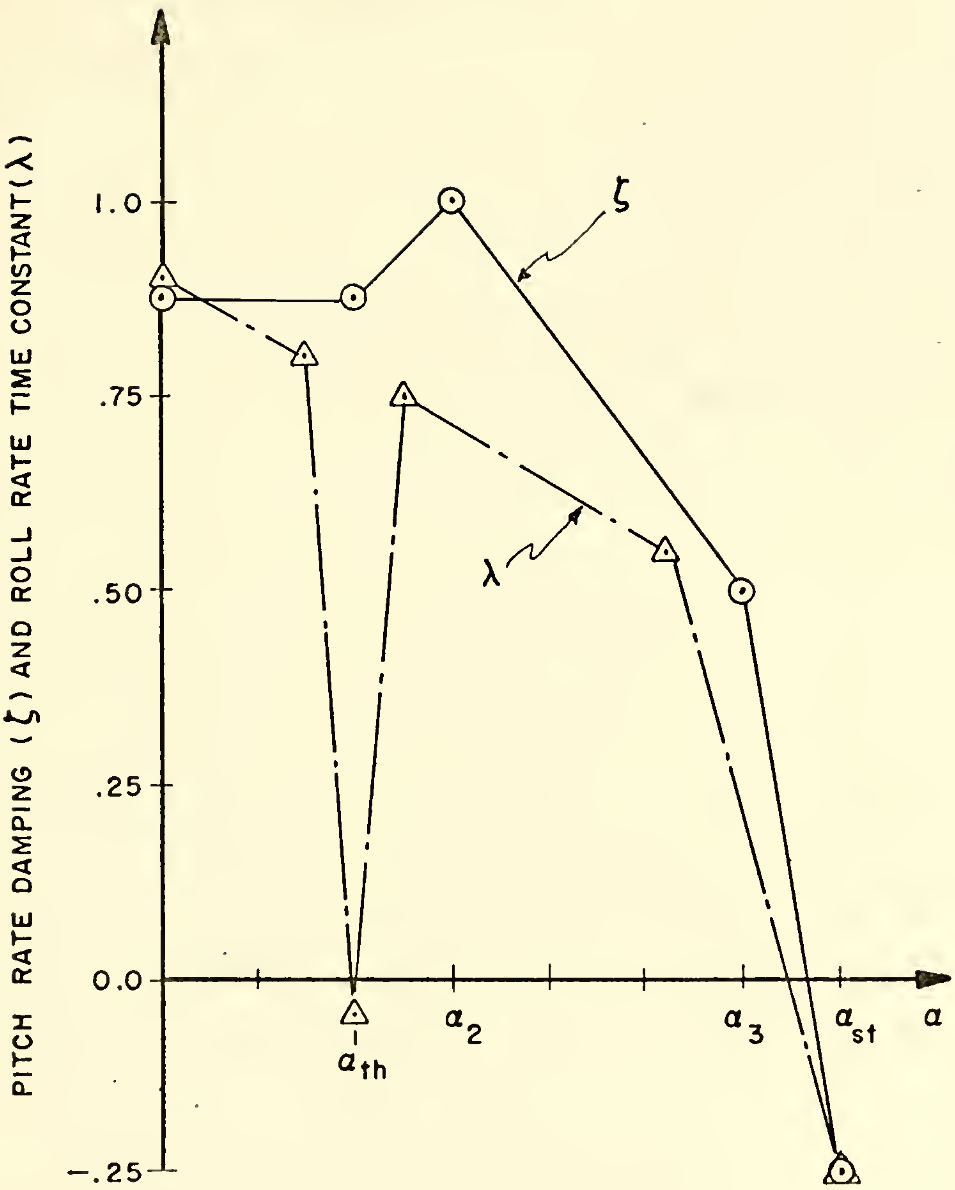


Figure 8. Variation of Various System Parameters with Angle of Attack.

Target Pitch Rate Forcing Function:

$\dot{\theta}$ = A1*A/2.153 + BIAS + T*A3

Target Roll Rate Forcing Function:

$\dot{\phi}$ = A2*B/2.153

Where:

A = VARY1 - VARY2

B = VARY1+ VARY2

VARY1 = .988*SIN(W1*DT) + .408*SIN(W3*DT)

VARY2 = .920*SIN(W2*DT) + .1087*SIN(W4*DT)

W2 = 2.5*W1

W3 = 2.0*W2

W4 = 1.5*W4

DT = 0.03 Secs

And the following:

Trk #	W1	A1	A2	A3	BIAS
1	.04712	-.3000	1.1000	.00070	0.2350
2	.07854	-.4000	0.9000	.00050	0.1500
3	.10995	-.3000	1.0000	.00180	0.1000
4	.14368	-.3000	0.9000	.00050	0.2300

Table II. Target Aircraft Forcing Functions

IV. RESULTS OF TESTING

A. LABORATORY TESTING

Tables III - VI list the data taken from each pilot in this portion of the testing and in Tables VII - X these data have been averaged by alpha window, display type and target track number. Finally in Figures 9 - 11 the primary performance parameters of percent successes, average rate error and penetration times which have been normalized with respect to performance, when no angle of attack display other than aircraft behavior was available, are presented. Alpha windows in which there are no entries for a particular type of display, eg. in window 2 of Fig. 9a there is no entry for "no display", indicate that there were either no successes in the case of percent successes and rate error or no failures in the case of penetration time for that particular window. If there were no "no display" entries available then the visual display data were used for normalizing and in the case where neither "no display" nor visual display were available the AAA/SWS was normalized with itself, eg. see Fig. 10b, window 3 for the first case and Fig. 9d, window 6 for the second.

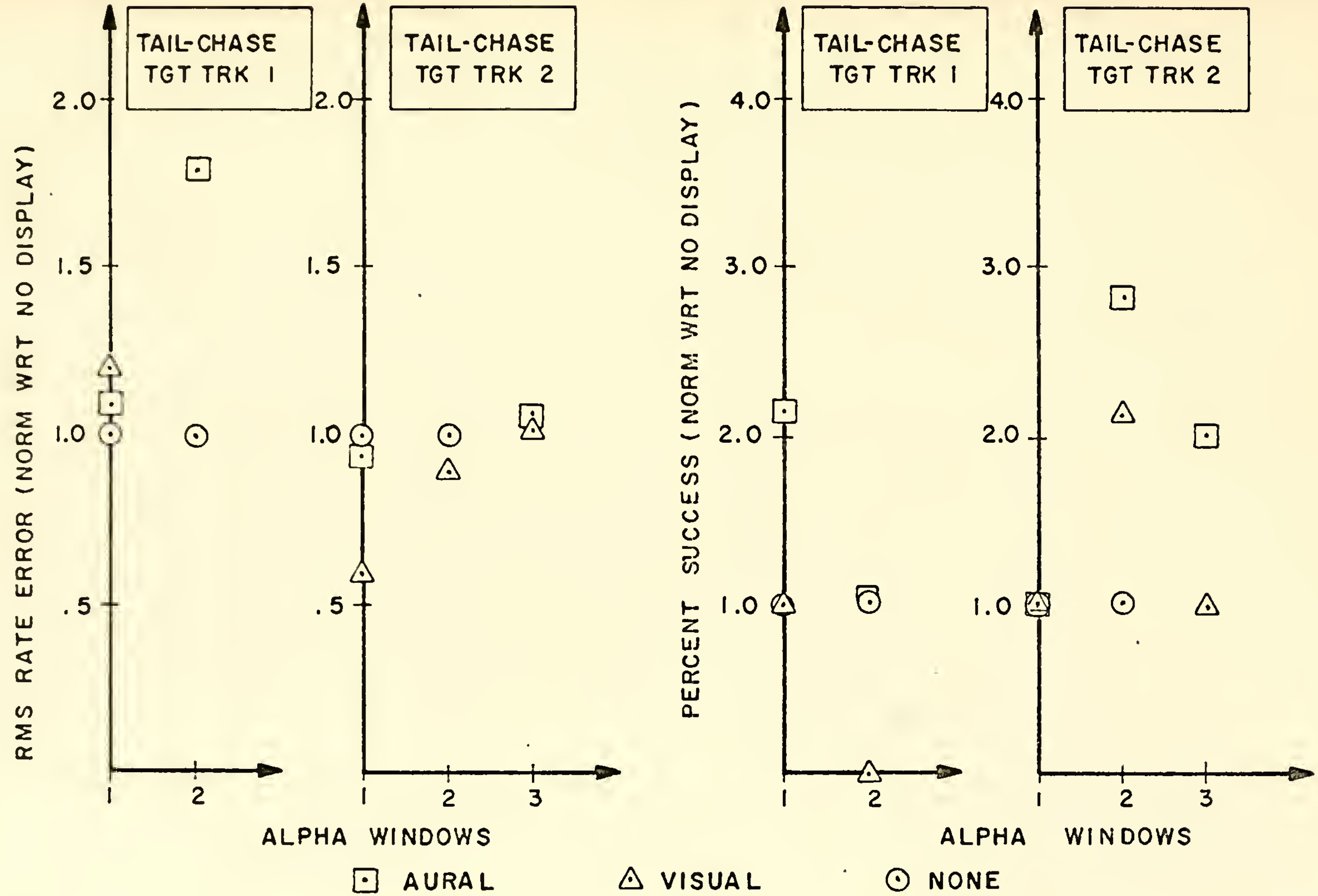
B. TESTING IN THE ACM SIMULATION

Percentage tracking times for aircraft with and without the AAA/SWS for the various target tracks are shown in Figure 12, while Figures 13 - 14 present time histories for angle of attack and elevator control with which comparisons of pilot performance between aircraft equipped with either the AAA/SWS

or visual display can be made. Pilot comments concerning the effects of the AAA/SWS on performance and confidence level in ACM are given in Table XI.

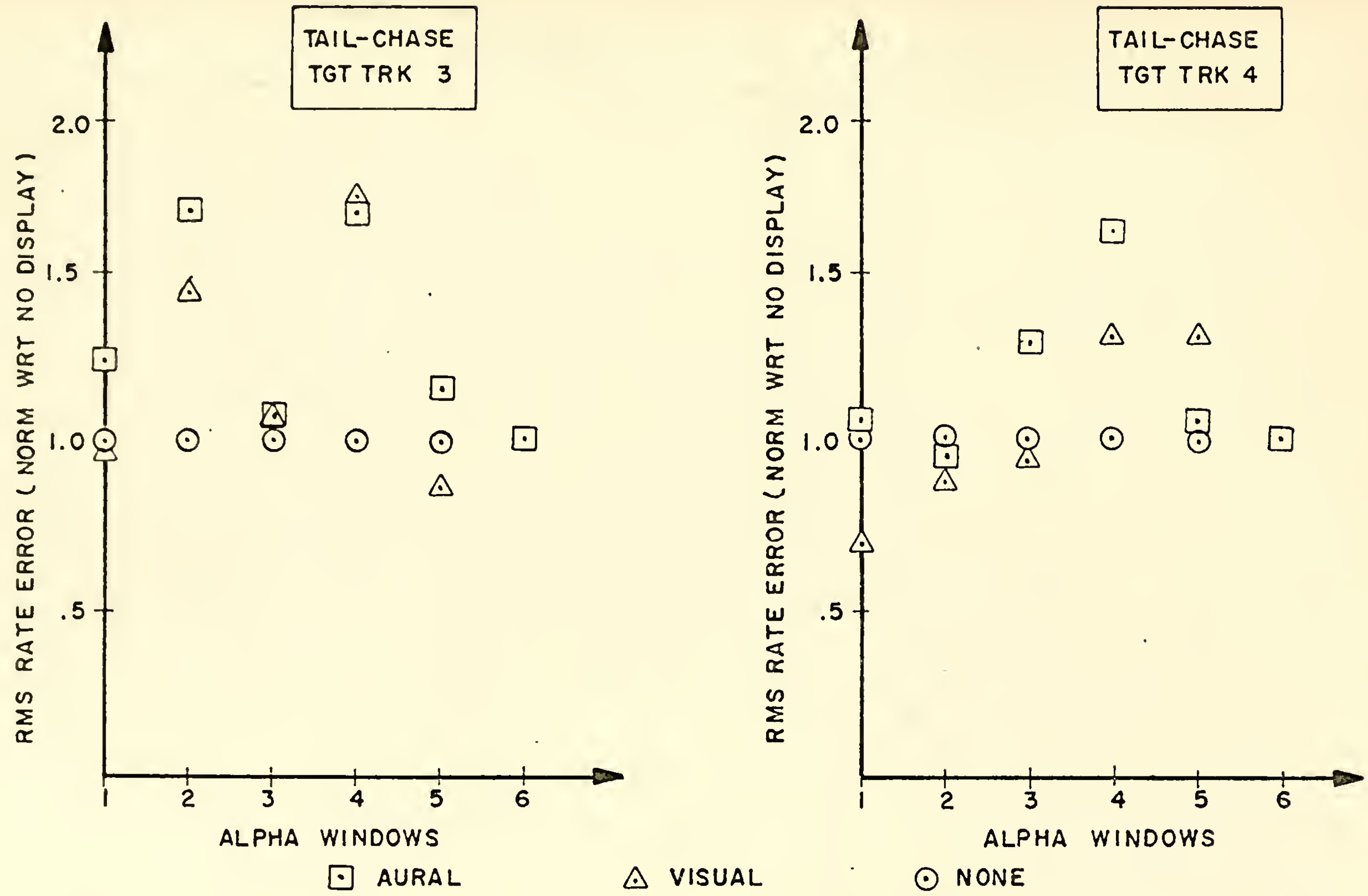
C. AIRCRAFT TESTING

Table XII lists specific pilot comments concerning the effects of the AAA/SWS on pilot performance, of ambient noise and two-way voice communications on reception and perception of the AAA/SWS display and the utility of the AAA/SWS in take-off and landing.

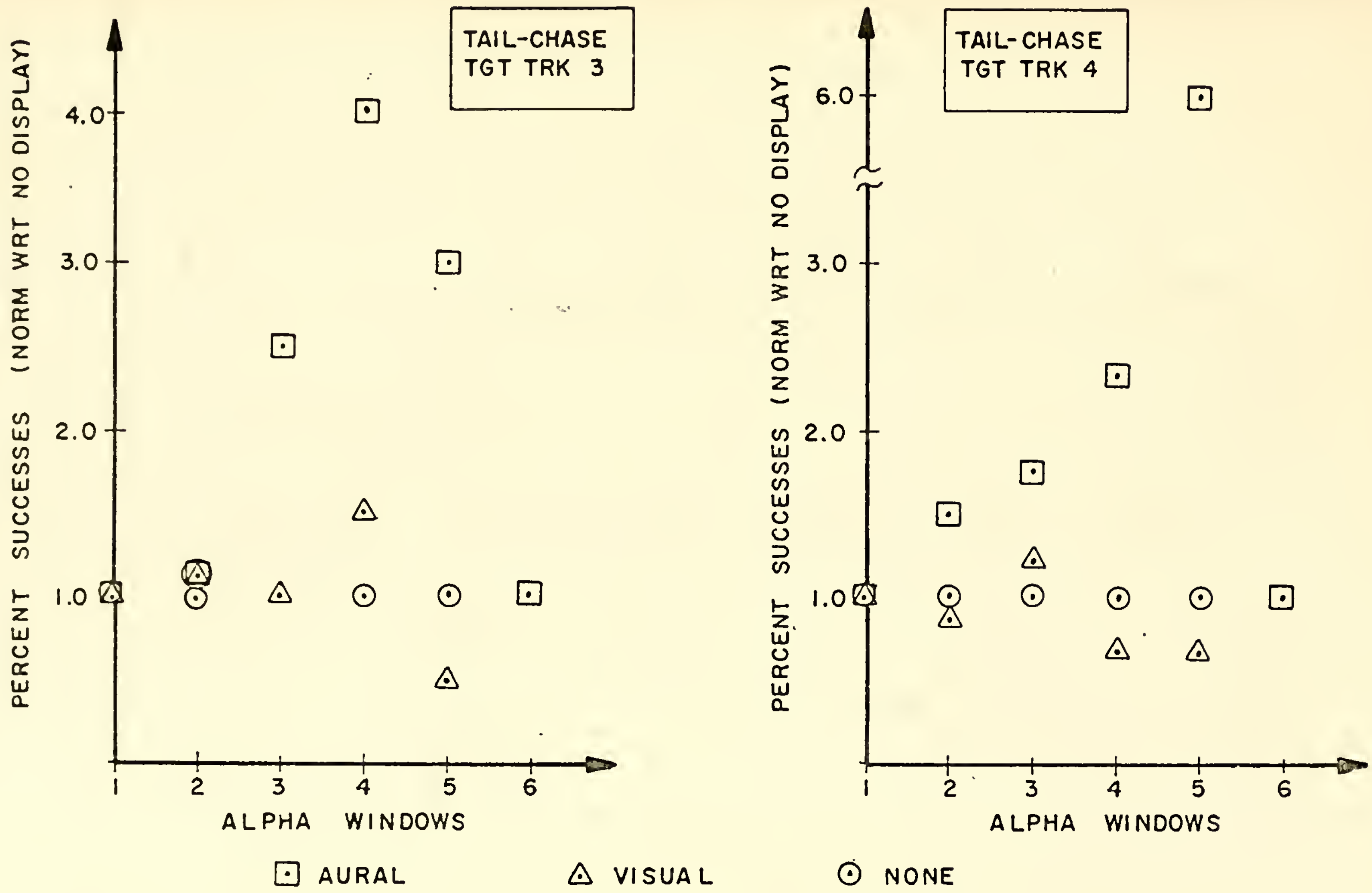


Figures 9a,b. Normalized RMS Rate Error for Successful Performance

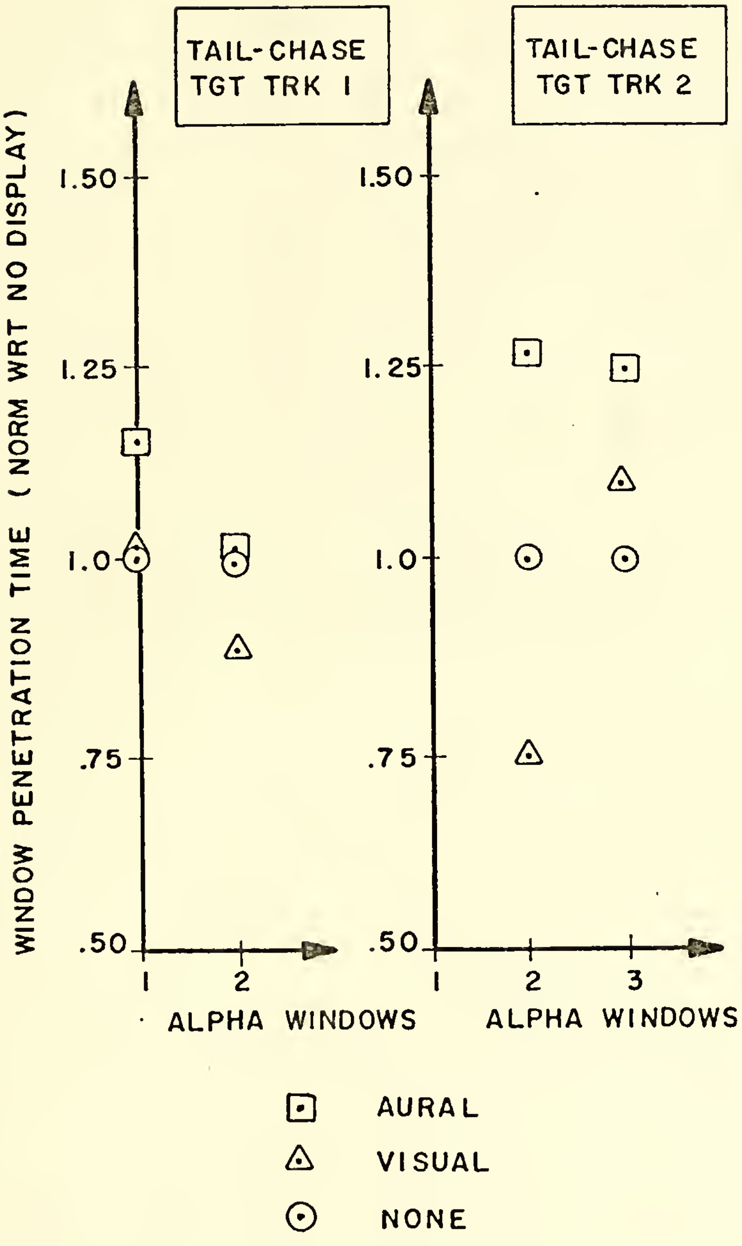
Figures 10a,b. Normalized Percent Success



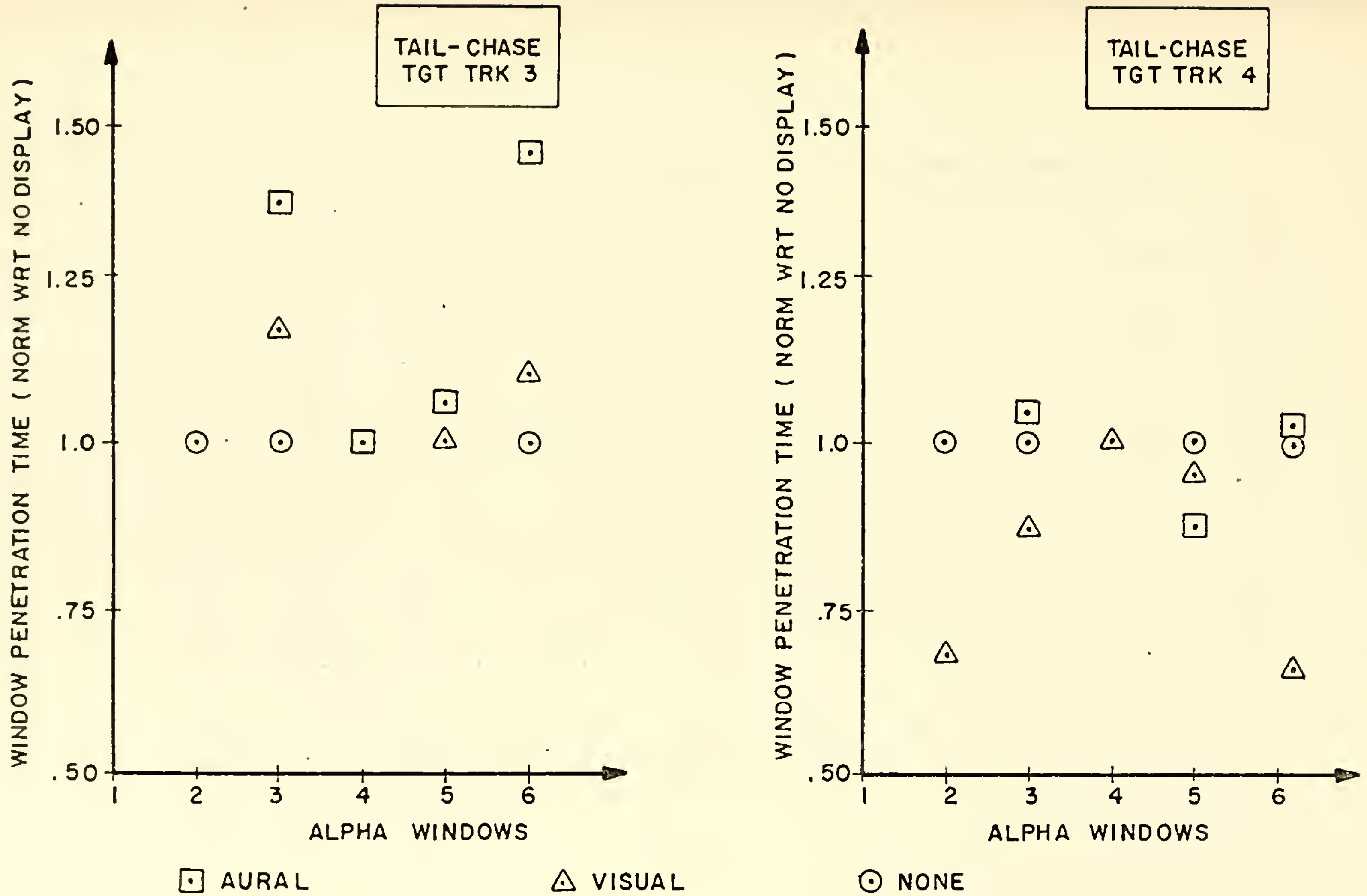
Figures 9c,d. Normalized RMS Rate Error for Successful Performance



Figures 10c,d. Normalized Percent Successes



Figures 11a,b. Normalized Avg. Window Penetration Time for Failure



Figures 11c,d. Normalized Avg. Window Penetration Time for Failure

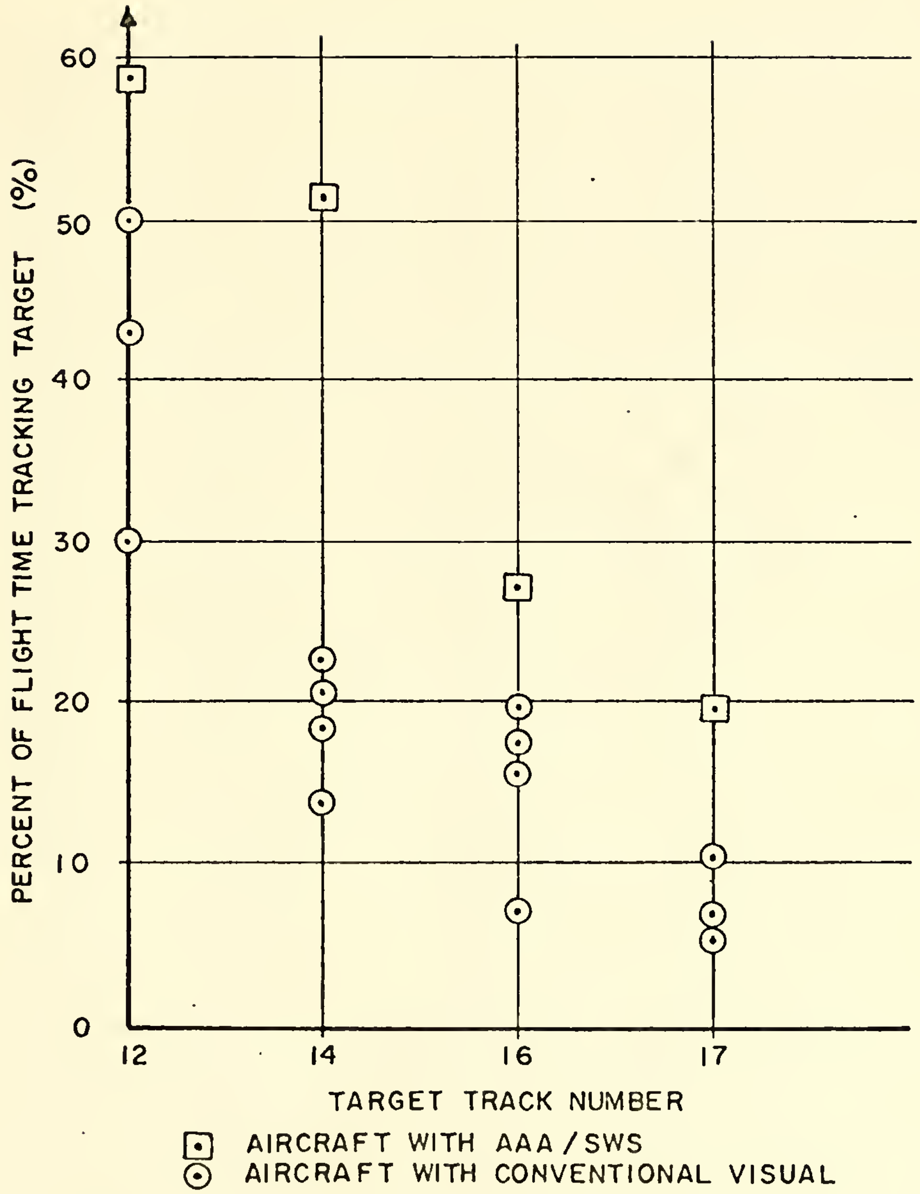


Figure 12. % Traching Time Comparison in ACM Testing

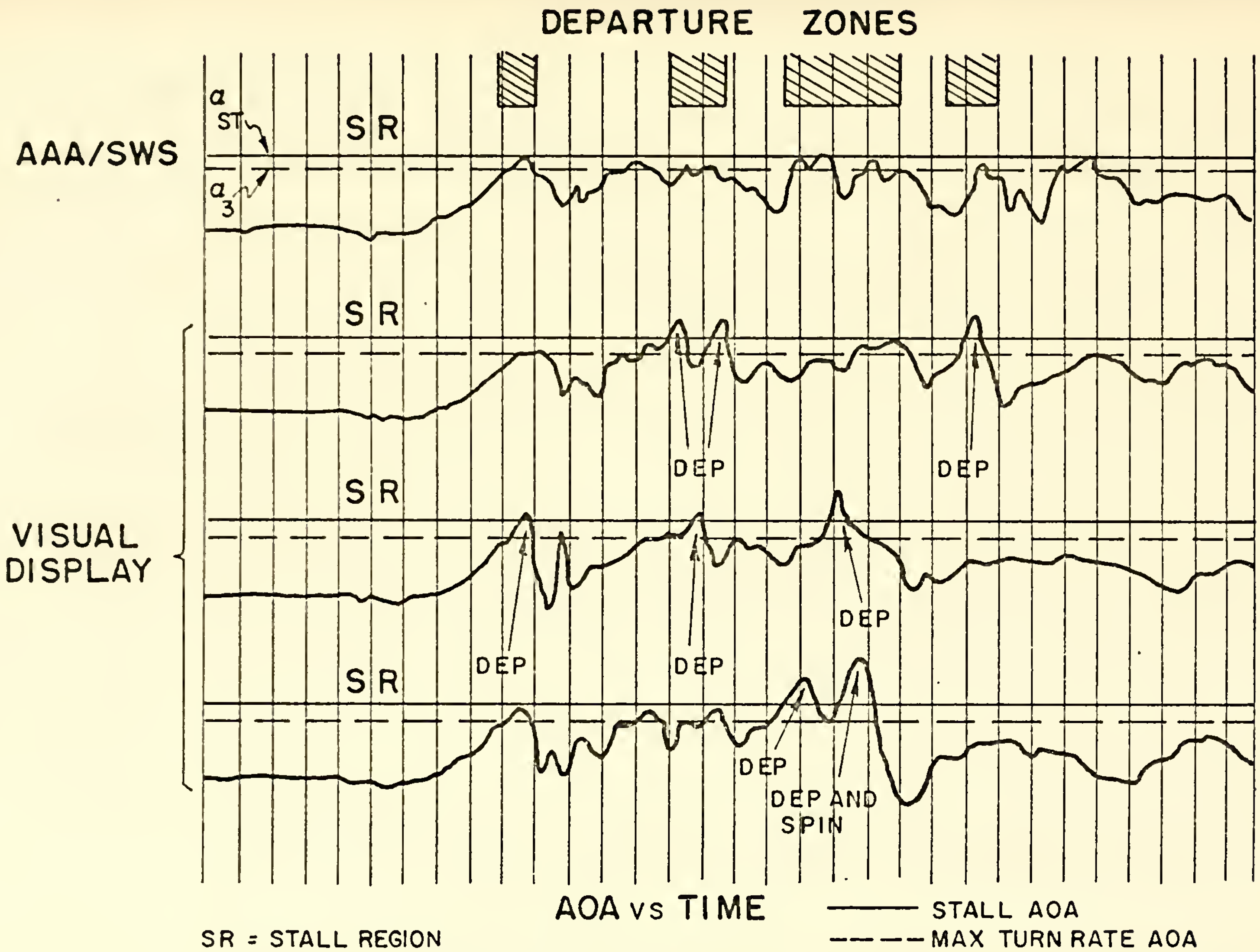
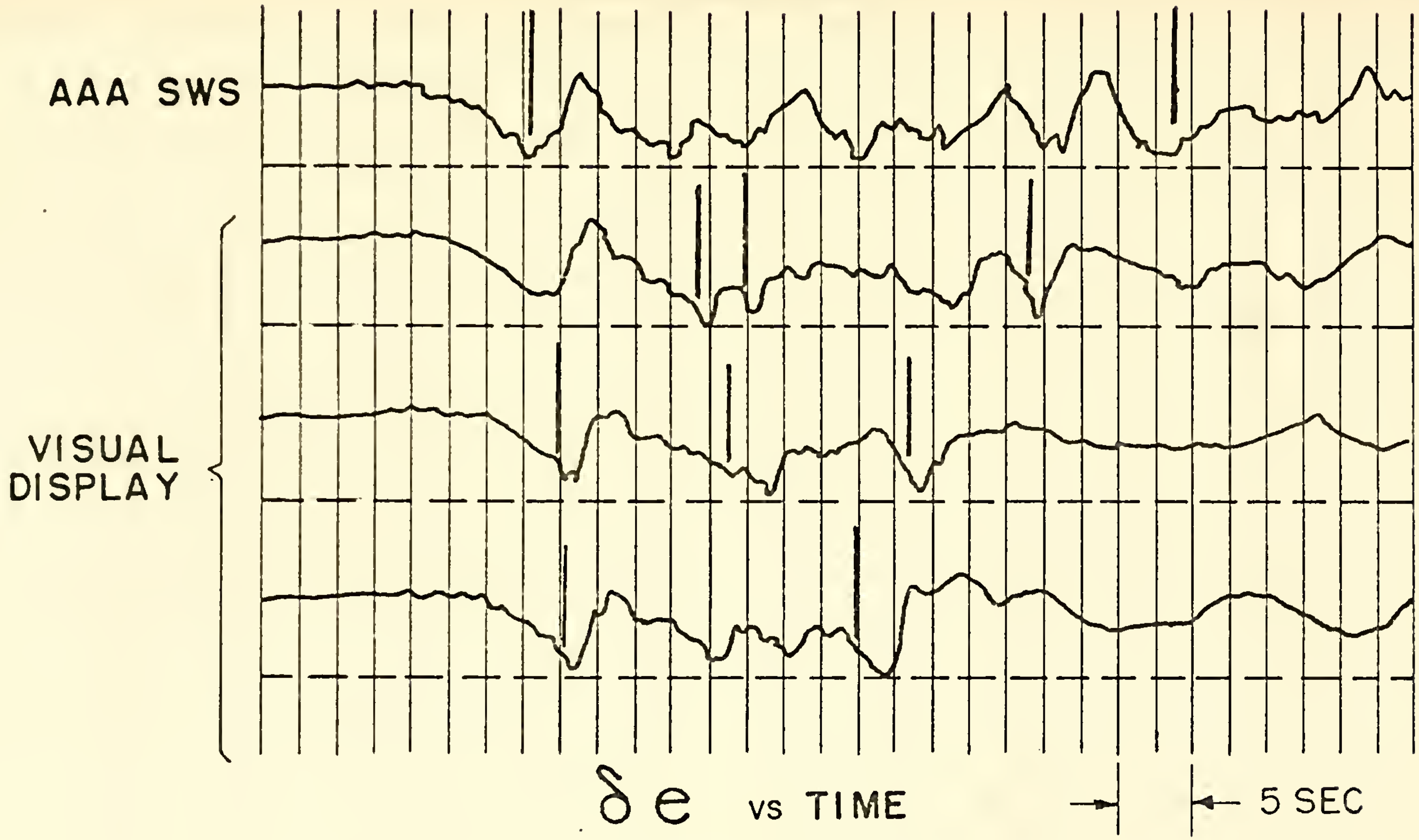


Figure 13. Comparison of Angle of Attack Time Histories for Aircraft With and Without AAA/SWS



Solid Vertical Lines indicate time at which AOA first $\geq$ Stall AOA. Note time delay before primary recovery, ie control stick forward, effected in aircraft equipped with Visual AOA display as compared with immediate recovery control in aircraft equipped with AAA/SWS.

– – – – Maximum Aft Control Stick

Figure 14. Comparison of Elevator Control time Histories for Aircraft With and Without AAA/SWS.

TARGET TRACK NUMBER 1

PLT NUM	TYPE DSP	WINDOW 1 TIME	WINDOW 1 RATE ERR	WINDOW 2 TIME	WINDOW 2 RATE ERR	WINDOW 3 TIME	WINDOW 3 RATE ERR	WINDOW 4 TIME	WINDOW 4 RATE ERR	WINDOW 5 TIME	WINDOW 5 RATE ERR	WINDOW 6 TIME	WINDOW 6 RATE ERR	NUM SCS	% DSP O-T
4	1	16.35	0.6789	19.74	0.9413	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
4	1	14.91	0.6138	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
5	1	13.14	1.3329	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
5	1	16.35	0.5471	20.67	0.6180	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	1	8.16	1.2524	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
6	1	16.05	0.8609	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
6	1	10.74	1.4319	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
6	1	16.35	0.6275	26.22	0.8557	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
7	1	12.54	0.4673	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
7	1	13.14	1.1846	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
7	1	11.64	1.0149	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
8	1	16.35	0.5895	24.27	0.9158	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
8	1	16.35	0.6034	20.64	1.0839	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
8	1	16.35	0.4655	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
8	1	11.70	1.0979	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
9	1	13.68	0.7187	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
9	1	12.78	0.7311	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
9	1	10.80	0.6832	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
4	2	15.81	0.7566	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	19.22
4	2	11.88	0.6369	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	11.88
4	2	10.17	0.9668	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	15.04
5	2	12.81	1.0573	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	22.61
5	2	13.53	0.8355	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	16.01
5	2	9.80	30.0000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	9.33
6	2	16.35	0.4240	21.57	0.9194	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	11.08
6	2	16.35	0.4038	19.11	0.5877	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	18.55
6	2	16.35	0.5546	21.24	0.9934	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	24.20
7	2	12.78	1.2364	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	14.50
7	2	16.17	0.5624	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	10.05
7	2	16.35	0.4647	24.78	0.7139	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	7.71
8	2	14.58	0.7621	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	19.86
8	2	13.83	0.6699	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	8.67
8	2	16.35	0.5311	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	13.10
9	2	8.10	0.4262	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	11.17
9	2	16.35	0.4981	13.68	0.3031	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	53.69
9	2	16.35	0.4667	21.09	0.8301	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	35.69
4	3	16.35	0.3926	15.60	0.3945	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
4	3	16.35	0.4427	21.69	0.5454	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
4	3	16.35	0.5659	24.03	0.6030	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
4	3	16.35	0.6790	25.44	0.6966	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	3	16.35	0.6502	25.65	0.5556	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	3	16.35	0.4869	19.11	0.9335	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	3	16.35	0.4664	21.03	0.5366	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
6	3	16.35	0.4855	23.58	0.5344	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
6	3	16.35	0.3604	20.64	0.5242	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
6	3	16.35	0.4523	28.14	0.5241	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
7	3	14.70	0.7583	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
7	3	13.44	0.5914	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
7	3	15.15	0.4311	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
8	3	16.35	0.4100	27.03	0.4994	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
8	3	16.35	0.5603	25.41	0.6784	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	3	16.35	0.6463	22.20	1.2454	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	3	16.35	0.5044	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	3	16.35	0.6938	15.72	0.7511	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0

Table III Results from Laboratory Testing (Individual)

TARGET TRACK NUMBER 2

PLT NUM	TYPE DSP	WINDOW 1 TIME	WINDOW 1 RATE ERR	WINDOW 2 TIME	WINDOW 2 RATE ERR	WINDOW 3 TIME	WINDOW 3 RATE ERR	WINDOW 4 TIME	WINDOW 4 RATE ERR	WINDOW 5 TIME	WINDOW 5 RATE ERR	WINDOW 6 TIME	WINDOW 6 RATE ERR	NUM SCS	% DSP D-T
4	1	6.18	0.5872	13.86	0.6811	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
4	1	6.18	0.3704	14.58	0.5207	7.14	0.7013	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
4	1	6.18	0.3037	14.58	0.3200	7.02	0.7317	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
4	1	6.18	0.3992	13.29	0.2308	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	1	6.18	0.2480	6.21	1.3621	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	1	6.18	0.4344	11.76	0.8430	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	1	6.18	0.5492	9.63	0.5555	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
6	1	6.18	0.2825	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
6	1	6.18	0.3565	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
6	1	6.18	0.3080	14.58	0.4386	8.97	0.5775	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	1	6.18	0.3408	11.46	1.5525	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
7	1	6.18	0.3584	14.58	0.3182	7.02	0.9548	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	1	6.18	0.3511	14.58	0.6520	9.90	0.9613	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	1	6.18	0.4314	14.58	0.6427	11.52	0.9045	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	1	6.18	0.3123	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	1	6.18	0.3225	11.22	0.6606	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	1	6.18	0.1927	9.60	0.4699	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	1	6.18	0.3475	13.74	0.6077	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
4	2	6.18	1.8216	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	8.45
4	2	6.18	1.8216	11.07	1.0023	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	3.45
4	2	6.18	0.7699	14.58	0.7035	10.41	0.8174	0.0	0.0	0.0	0.0	0.0	0.0	2	19.69
5	2	6.18	0.5559	14.58	0.5277	10.83	1.6694	0.0	0.0	0.0	0.0	0.0	0.0	2	31.66
5	2	6.18	0.5460	14.58	0.8968	7.95	0.5195	0.0	0.0	0.0	0.0	0.0	0.0	2	9.51
5	2	6.18	0.2621	14.58	0.5034	7.83	0.6995	0.0	0.0	0.0	0.0	0.0	0.0	2	5.81
6	2	6.18	0.2515	14.58	0.2879	11.64	0.7470	0.0	0.0	0.0	0.0	0.0	0.0	2	14.57
6	2	6.18	0.4474	14.58	0.3178	10.98	0.9060	0.0	0.0	0.0	0.0	0.0	0.0	3	10.61
6	2	6.18	0.3427	14.58	0.4761	8.73	0.4979	0.0	0.0	0.0	0.0	0.0	0.0	2	12.98
7	2	6.18	0.4658	13.08	0.3469	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2	13.05
7	2	6.18	0.3851	14.58	0.2615	8.76	0.7205	0.0	0.0	0.0	0.0	0.0	0.0	3	9.41
7	2	6.18	0.3047	14.58	0.5178	9.15	1.3258	0.0	0.0	0.0	0.0	0.0	0.0	2	5.78
8	2	6.18	0.4256	12.69	0.5110	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	25.33
8	2	6.18	0.5254	14.58	0.5755	9.84	0.8085	0.0	0.0	0.0	0.0	0.0	0.0	2	23.59
8	2	6.18	0.4041	14.58	0.4756	9.63	1.1333	0.0	0.0	0.0	0.0	0.0	0.0	2	25.62
9	2	6.18	0.3601	0.57	1.5685	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	10.73
9	2	6.18	0.5045	8.13	0.2388	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	34.83
9	2	6.18	0.4051	14.58	1.0781	9.58	2.4008	0.0	0.0	0.0	0.0	0.0	0.0	2	9.92
4	3	6.18	0.3804	14.58	0.4318	10.96	1.0765	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
4	3	6.18	0.3402	14.58	0.5060	11.07	0.8918	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
5	3	6.18	0.3623	14.58	0.5596	9.90	1.1150	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
5	3	6.18	0.4743	14.58	0.7823	11.13	0.9051	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
5	3	6.18	0.3798	14.58	0.2789	11.16	0.8120	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
6	3	6.18	0.2160	14.58	0.5363	10.23	0.6454	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
6	3	6.18	0.3826	14.58	0.3962	10.56	0.7377	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
6	3	6.18	0.2355	14.58	0.4161	11.07	0.8351	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
7	3	6.18	0.3708	14.58	0.4381	9.81	0.7720	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	3	6.18	0.3659	13.74	3.1780	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
7	3	6.18	0.3486	14.58	0.2881	10.92	0.8924	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	3	6.18	0.4727	14.58	0.5195	10.38	1.0426	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	3	6.18	0.3980	14.58	0.3776	11.46	0.9896	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	3	6.18	0.5013	14.58	0.2570	11.13	0.7426	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
8	3	6.18	0.4268	14.58	0.3049	9.33	0.7412	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
9	3	6.18	0.4072	14.58	0.8870	10.71	0.9877	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	3	6.18	0.2115	14.58	0.6235	10.20	0.8560	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	3	6.18	0.4394	14.58	0.8329	10.56	0.8122	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0

Table IV   Results from Laboratory Testing (Individual)

TARGET TRACK NUMBER 3

PLT NUM	TYPE DSP	WINDOW 1 TIME	WINDOW 1 RATE ERR	WINDOW 2 TIME	WINDOW 2 RATE ERR	WINDOW 3 TIME	WINDOW 3 RATE ERR	WINDOW 4 TIME	WINDOW 4 RATE ERR	WINDOW 5 TIME	WINDOW 5 RATE ERR	WINDOW 6 TIME	WINDOW 6 RATE ERR	NUM SCS	% DSP O-T
4	1	1.35	0.2854	3.84	0.6099	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
4	1	1.35	2.0998	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
5	1	1.35	0.3167	6.06	0.2145	4.68	0.2349	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
5	1	1.35	0.1588	6.06	0.6682	9.09	0.9335	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
5	1	1.35	0.1919	6.06	0.3702	7.44	1.2226	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
6	1	1.35	0.0612	6.06	0.1123	10.56	1.0848	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
6	1	1.35	0.2498	6.06	0.3911	12.09	0.8169	3.30	0.9151	10.44	0.0287	0.0	0.0	5	0.0
6	1	1.35	0.1365	6.06	0.2072	6.96	1.7698	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	1	1.35	0.1791	6.06	0.2034	7.92	2.1033	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	1	1.35	0.1311	6.06	1.0924	9.42	1.1693	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	1	1.35	0.2215	6.06	0.2068	8.73	0.7498	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
8	1	1.35	0.0561	6.06	0.2902	7.89	1.4538	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	1	1.35	0.1762	6.06	0.4617	8.52	1.0247	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
8	1	1.35	0.1523	6.06	0.2726	12.09	0.7787	3.30	0.2230	10.44	1.1482	8.64	1.6273	5	0.0
8	1	1.35	0.0826	6.06	0.3875	7.77	1.1780	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	1	1.35	0.1844	6.06	0.5862	7.77	1.5717	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	1	1.35	0.3000	6.06	0.5343	1.59	0.8292	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	1	1.35	0.0845	6.06	0.5509	9.48	0.7310	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
4	2	1.35	0.1645	6.06	0.4684	12.09	1.0337	3.30	0.3817	4.59	1.2401	0.0	0.0	4	28.41
4	2	1.35	0.3011	6.06	0.2118	7.95	0.8664	0.0	0.0	0.0	0.0	0.0	0.0	2	22.55
4	2	1.35	0.2773	6.06	0.4362	12.09	0.7729	3.30	0.2752	8.46	0.6486	0.0	0.0	4	38.55
4	2	1.35	0.9780	6.06	0.1848	9.42	0.7982	0.0	0.0	0.0	0.0	0.0	0.0	2	41.65
5	2	1.35	0.1905	6.06	0.2516	6.96	0.5657	0.0	0.0	0.0	0.0	0.0	0.0	2	20.16
5	2	1.35	0.3495	6.06	0.1447	9.21	0.7074	0.0	0.0	0.0	0.0	0.0	0.0	2	7.95
5	2	1.35	0.1156	6.06	0.1946	8.55	1.2167	0.0	0.0	0.0	0.0	0.0	0.0	2	6.86
6	2	1.35	0.2113	6.06	0.4895	12.09	0.9449	3.30	0.3274	10.44	1.2065	9.48	1.0523	5	14.12
6	2	1.35	0.2355	6.06	0.3726	12.09	0.6585	0.0	0.0	0.0	0.0	0.0	0.0	3	12.51
6	2	1.35	0.0687	6.06	0.3390	12.09	0.8103	3.30	0.3978	7.41	1.4644	0.0	0.0	4	14.38
7	2	1.35	0.0839	6.06	0.1687	9.54	1.0440	0.0	0.0	0.0	0.0	0.0	0.0	2	11.19
7	2	1.35	0.3604	6.06	0.2335	11.16	0.6252	0.0	0.0	0.0	0.0	0.0	0.0	2	3.62
7	2	1.35	0.1598	6.06	0.1324	9.60	0.7339	0.0	0.0	0.0	0.0	0.0	0.0	2	5.52
8	2	1.35	0.3604	6.06	0.2335	11.16	0.6252	0.0	0.0	0.0	0.0	0.0	0.0	2	3.62
8	2	1.35	0.3315	6.06	0.1779	8.16	0.8651	0.0	0.0	0.0	0.0	0.0	0.0	2	11.94
9	2	1.35	0.2742	6.06	0.2957	6.33	0.7786	0.0	0.0	0.0	0.0	0.0	0.0	2	19.03
9	2	1.35	0.2825	6.06	0.1963	8.85	1.3326	0.0	0.0	0.0	0.0	0.0	0.0	2	17.81
9	2	1.35	0.2317	6.06	0.8664	9.00	0.9422	0.0	0.0	0.0	0.0	0.0	0.0	2	21.69
4	3	1.35	0.5103	6.06	0.2325	10.74	0.7550	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
5	3	1.35	0.1346	6.06	0.2873	12.09	0.8902	3.30	0.4151	8.34	1.0316	0.0	0.0	4	0.0
5	3	1.35	0.2161	6.06	0.1991	10.71	1.2565	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
5	3	1.35	0.1191	6.06	0.1345	11.82	0.7437	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
6	3	1.35	0.2449	6.06	0.2004	12.09	0.7026	3.30	0.3820	10.44	0.6744	11.55	1.1750	5	0.0
6	3	1.35	0.7608	6.06	0.1487	12.09	0.6599	3.30	0.4867	8.28	1.6790	0.0	0.0	5	0.0
6	3	1.35	0.0714	6.06	0.1313	12.09	0.7566	3.30	0.1928	7.92	0.8773	0.0	0.0	5	0.0
7	3	1.35	0.1938	6.06	0.2546	11.40	0.9866	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	3	1.35	0.0824	6.06	0.2347	12.09	0.7068	2.10	1.4418	0.0	0.0	0.0	0.0	3	0.0
7	3	1.35	0.2546	6.06	0.1170	12.09	0.6470	3.30	0.4348	8.46	1.3653	0.0	0.0	4	0.0
8	3	1.35	0.1721	6.06	0.1760	7.20	1.2205	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	3	1.35	0.2200	6.06	0.1747	9.09	1.1482	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	3	1.35	0.0778	6.06	0.1553	12.09	0.6220	3.30	0.4033	10.44	0.6015	14.13	1.1270	5	0.0
8	3	1.35	0.0898	6.06	0.1796	12.09	1.3556	3.30	0.1492	10.44	0.9191	12.65	1.0463	6	0.0
8	3	1.35	0.0509	6.06	0.1776	12.09	0.8775	3.30	0.2456	10.44	0.6246	12.75	1.1877	5	0.0
9	3	1.35	0.4003	6.06	0.5196	10.77	0.8103	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	3	1.35	0.0820	6.06	0.4696	10.32	0.7750	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	3	1.35	0.4003	6.06	0.5196	10.77	0.8103	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0

Table V Results from Laboratory Testing (Individual)

TARGET TRACK NUMBER 4

PLT NUM	TYPE DSP	WINDOW 1 TIME	WINDOW 1 RATE ERR	WINDOW 2 TIME	WINDOW 2 RATE ERR	WINDOW 3 TIME	WINDOW 3 RATE ERR	WINDOW 4 TIME	WINDOW 4 RATE ERR	WINDOW 5 TIME	WINDOW 5 RATE ERR	WINDOW 6 TIME	WINDOW 6 RATE ERR	NUM SCS	% DSP O-T
4	1	4.17	0.5825	9.72	0.2983	9.24	0.6445	5.49	0.4998	11.34	1.0242	0.0	0.0	4	0.0
4	1	4.17	0.5184	9.72	0.5749	9.24	0.6901	5.49	0.4658	11.85	0.4986	0.0	0.0	5	0.0
4	1	4.17	0.9191	9.72	0.7246	9.24	1.0533	5.49	0.9041	9.81	0.7739	0.0	0.0	4	0.0
5	1	4.17	0.4027	9.72	0.4797	6.96	0.6413	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
5	1	4.17	0.2756	9.72	0.3086	9.24	0.9371	5.49	1.0427	11.28	1.2503	0.0	0.0	4	0.0
5	1	4.17	0.4554	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
6	1	4.17	0.5383	9.72	0.7242	8.13	0.9097	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
6	1	4.17	0.1930	0.99	1.0280	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
6	1	4.17	0.3497	9.72	0.4901	7.62	0.9549	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
7	1	4.17	0.5967	4.86	1.0264	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
7	1	4.17	0.3454	9.72	0.5079	8.34	1.9992	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
7	1	4.17	0.3420	9.72	0.3216	6.54	1.5381	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
8	1	4.17	0.4579	9.72	0.3916	9.24	1.8014	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
8	1	4.17	0.2816	9.72	1.0948	9.24	0.8407	5.49	0.9375	11.85	0.9619	8.97	0.8944	5	0.0
8	1	4.17	0.3559	9.72	0.4396	9.24	0.8710	5.49	0.7190	11.85	0.5319	9.36	1.3829	5	0.0
9	1	4.17	0.6083	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	1	4.17	0.3747	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
9	1	4.17	0.2891	9.03	0.5680	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0
4	2	4.17	1.3823	9.00	0.7832	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	56.51
4	2	4.17	0.3338	7.74	0.6038	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	23.81
4	2	4.17	1.0517	9.72	0.7060	9.24	0.6704	5.49	0.4791	10.29	0.6255	0.0	0.0	4	23.08
5	2	4.17	0.3350	9.72	0.4549	9.24	1.1726	4.62	0.5823	0.0	0.0	0.0	0.0	3	25.44
5	2	4.17	0.4943	4.26	1.6173	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	9.61
5	2	4.17	0.3505	9.72	0.8919	9.24	0.8909	3.69	0.3897	0.0	0.0	0.0	0.0	3	7.14
6	2	4.17	0.3750	9.72	0.3300	9.24	0.6035	0.0	0.0	0.0	0.0	0.0	0.0	3	11.42
6	2	4.17	0.2526	9.72	0.5041	9.24	0.9518	5.49	0.4328	0.0	0.0	0.0	0.0	4	16.93
6	2	4.17	0.2424	9.72	1.1439	6.57	0.8685	0.0	0.0	0.0	0.0	0.0	0.0	2	12.00
7	2	4.17	0.3864	9.72	0.2572	9.24	1.4256	0.0	0.0	0.0	0.0	0.0	0.0	3	10.63
7	2	4.17	0.2814	5.61	1.9576	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	7.91
7	2	4.17	0.4172	9.72	0.3408	9.24	1.5300	0.0	0.0	0.0	0.0	0.0	0.0	3	9.32
8	2	4.17	0.5611	9.72	0.6674	9.24	0.8744	5.49	0.7817	7.17	0.5591	0.0	0.0	5	24.20
8	2	4.17	0.5654	9.72	0.6911	9.24	0.7299	5.49	0.6339	11.85	0.4641	6.06	0.4140	5	14.02
8	2	4.17	0.3151	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	11.21
9	2	4.17	0.2543	8.07	0.8098	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	23.69
9	2	4.17	1.2462	9.72	0.5572	4.74	1.4437	0.0	0.0	0.0	0.0	0.0	0.0	3	31.96
9	2	4.17	2.5640	86.70	5.4600	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	33.45
4	3	4.17	0.5693	9.72	0.4176	9.24	0.6874	5.49	0.8288	0.60	1.5952	0.0	0.0	4	0.0
4	3	4.17	0.4642	9.72	0.8359	9.24	1.1653	5.49	0.3461	11.85	0.9685	0.0	0.0	5	0.0
4	3	4.17	0.4597	9.72	0.4135	9.24	0.7517	5.49	0.8946	11.85	1.0383	10.86	0.8739	6	0.0
4	3	4.17	0.3666	9.72	0.3711	9.24	0.7193	5.49	0.4686	11.85	0.6190	9.00	1.1032	5	0.0
5	3	4.17	0.4807	9.72	0.6719	9.24	0.9073	5.49	0.4664	11.85	0.8099	0.0	0.0	5	0.0
5	3	4.17	0.5767	9.72	0.4135	9.24	0.6042	5.49	0.3729	11.85	0.6197	0.0	0.0	5	0.0
5	3	4.17	0.3195	9.72	0.3626	9.24	0.6527	5.49	0.5189	11.85	0.4585	10.86	0.7167	6	0.0
6	3	4.17	0.4129	9.72	0.5378	9.24	0.6696	5.49	0.4674	11.85	0.5706	8.82	0.9447	5	0.0
6	3	4.17	0.3574	9.72	0.3637	9.24	0.7228	5.49	0.4524	9.45	0.6909	0.0	0.0	4	0.0
6	3	4.17	0.4733	9.72	0.4534	9.24	0.6611	5.49	0.3828	11.85	0.6125	10.86	0.9226	6	0.0
7	3	4.17	0.5090	9.72	0.7000	9.24	1.1628	5.49	0.3415	11.85	0.5303	9.45	1.0629	5	0.0
7	3	4.17	0.3483	9.72	0.2353	9.24	0.6265	5.49	0.3155	11.85	0.4618	10.86	0.8120	6	0.0
7	3	4.17	0.2305	9.72	0.3099	9.24	0.5611	5.49	0.4076	11.85	0.4292	10.14	0.8657	5	0.0
8	3	4.17	0.3544	9.72	0.2580	9.24	0.7425	5.49	0.6853	11.85	0.5374	10.86	0.9898	6	0.0
8	3	4.17	0.3737	9.72	1.2891	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	3	4.17	0.7633	9.72	0.2329	9.24	0.5885	5.49	0.4423	0.0	0.0	0.0	0.0	4	0.0
9	3	4.17	0.3756	9.72	0.6652	7.71	1.0473	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0
9	3	4.17	0.2405	9.72	0.4444	7.83	0.5843	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0

Table VI Results from Laboratory Testing (Individual)

TARGET TRACK NUMBER 1

TYPE AOA DISPLAY: NONE

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	16.35	19.74	0.0	0.0	0.0	0.0
AVG RATE ERR	0.5685	0.9413	0.0	0.0	0.0	0.0
TOT NUM SCS	7	1	0	0	0	0
FAILURE DATA:						
AVG PEN TIME	12.43	22.95	0.0	0.0	0.0	0.0
AVG RATE ERR	0.9929	0.8683	0.0	0.0	0.0	0.0

Table VIIa   Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 1

TYPE AOA DISPLAY: VISUAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	16.35	0.0	0.0	0.0	0.0	0.0
AVG RATE ERR	0.4776	0.0	0.0	0.0	0.0	0.0
TOT NUM SCS	7	0	0	0	0	0
FAILURE DATA:						
AVG PEN TIME	12.68	20.24	0.0	0.0	0.0	0.0
AVG RATE ERR	3.4464	0.7329	0.0	0.0	0.0	0.0

Table VIIb Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 1

TYPE AOA DISPLAY: AURAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDCW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	16.35	20.64	0.0	0.0	0.0	0.0
AVG RATE ERR	0.5199	0.5242	0.0	0.0	0.0	0.0
TOT NUM SCS	15	1	0	0	0	0
FAILURE DATA:						
AVG PEN TIME	14.43	22.66	0.0	0.0	0.0	0.0
AVG RATE ERR	0.5936	0.6529	0.0	0.0	0.0	0.0

Table VIIc Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 2

TYPE AOA DISPLAY: NONE

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	6.18	14.58	0.0	0.0	0.0	0.0
AVG RATE ERR	0.3609	0.4820	0.0	0.0	0.0	0.0
TOT NUM SCS	18	6	0	0	0	0
FAILURE DATA:						
AVG PEN TIME	0.0	11.20	8.59	0.0	0.0	0.0
AVG RATE ERR	0.0	0.7737	0.8052	0.0	0.0	0.0

Table VIIIa Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 2

TYPE AOA DISPLAY: VISUAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	6.18	14.58	10.98	0.0	0.0	0.0
AVG RATE ERR	0.5888	0.5360	0.8132	0.0	0.0	0.0
TOT NUM SCS	18	13	2	0	0	0
FAILURE DATA:						
AVG PEN TIME	0.0	8.11	9.46	0.0	0.0	0.0
AVG RATE ERR	0.0	0.8301	1.0639	0.0	0.0	0.0

Table VIIIb Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 2

TYPE AOA DISPLAY: AURAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	6.18	14.58	11.13	0.0	0.0	0.0
AVG RATE ERR	0.3731	0.4992	0.7641	0.0	0.0	0.0
TOT NUM SCS	18	17	4	0	0	0
FAILURE DATA:						
AVG PEN TIME	0.0	13.74	10.65	0.0	0.0	0.0
AVG RATE ERR	0.0	3.1780	0.9229	0.0	0.0	0.0

Table VIIIc Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 3

TYPE AOA DISPLAY: NONE

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	1.35	6.06	12.09	3.30	10.44	0.0
AVG RATE ERR	0.2812	0.4093	0.8425	0.5690	1.0384	0.0
TOT NUM SCS	18	16	4	2	2	0
FAILURE DATA:						
AVG PEN TIME	0.0	3.84	7.55	0.0	0.0	8.64
AVG RATE ERR	0.0	0.6099	1.1902	0.0	0.0	1.6273

Table IXa Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 3

TYPE AOA DISPLAY: VISUAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	1.35	6.06	12.09	3.30	10.44	0.0
AVG RATE ERR	0.2765	0.3026	0.8441	0.3455	1.2065	C.0
TOT NUM SCS	18	18	5	4	1	0
FAILURE DATA:						
AVG PEN TIME	0.0	0.0	8.91	0.0	6.82	9.48
AVG RATE ERR	0.0	0.0	0.8539	0.0	1.1177	1.0523

Table IXb Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 3

TYPE AOA DISPLAY: AURAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	1.35	6.06	12.09	3.30	10.44	12.66
AVG RATE ERR	0.2267	0.2423	0.7973	0.3393	0.8960	1.0463
TOT NUM SCS	18	18	10	8	6	1
FAILURE DATA:						
AVG PEN TIME	0.0	0.0	10.26	2.10	8.40	12.81
AVG RATE ERR	0.0	0.0	0.9689	1.4418	1.1984	1.1632

Table IXc Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 4

TYPE AOA DISPLAY: NONE

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	4.17	9.72	9.24	5.49	11.85	0.0
AVG RATE ERR	0.4381	0.5297	0.9741	0.7615	0.6641	0.0
TOT NUM SCS	18	12	8	6	3	0
FAILURE DATA:						
AVG PEN TIME	0.0	4.96	7.49	0.0	10.81	9.16
AVG RATE ERR	0.0	0.8741	1.2721	0.0	1.0161	1.1386

Table Xa Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 4

TYPE AOA DISPLAY: VISUAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	4.17	9.72	9.24	5.49	11.85	0.0
AVG RATE ERR	0.6338	0.5950	1.0293	0.5819	0.5116	0.0
TOT NUM SCS	18	11	10	4	2	0
FAILURE DATA:						
AVG PEN TIME	0.0	20.23	6.57	4.15	10.29	6.06
AVG RATE ERR	0.0	1.8728	0.8685	0.4860	0.6255	0.4140

Table Xb Results from Laboratory Testing (Averages)

TARGET TRACK NUMBER 4

TYPE AOA DISPLAY: AURAL

	WINDOW 1	WINDOW 2	WINDOW 3	WINDOW 4	WINDOW 5	WINDOW 6
SUCCESS DATA:						
AVG TIME	4.17	9.72	9.24	5.49	11.85	10.86
AVG RATE ERR	0.4264	0.5020	0.7482	0.4927	0.6380	0.8630
TOT NUM SCS	18	18	15	15	12	5
FAILURE DATA:						
AVG PEN TIME	0.0	0.0	7.77	0.0	5.02	9.36
AVG RATE ERR	0.0	0.0	0.8158	0.0	1.1430	0.9941

Table Xc Results from Laboratory Testing (Averages)

Subject	
Effects of AAA/SWS on pilot performance and confidence level	1. AAA/SWS definitely enables pilot to locate AOA's and recognize direction and rate of movement. 2. Can better tell when to pull nose up to track target and gauge how hard to pull using AAA/SWS whereas have to be more conservative and feel aircraft out without it. 3. Helps to get back into "saddle" after losing position because able to go directly to maximum performance AOA in contrast to "fishing" for the same AOA without it. 4. Using AAA/SWS able to track target under conditions in which had previously departed or been unable to without it.
Ability of AAA/SWS to provide warning of approach to and passage through stall AOA	1. Solid FM tone prior to stall AOA definitely warns pilot that departure imminent and thereby allows him to avoid it. 2. In the event that stall AOA is exceeded the step in frequency warns of the occurance and cues the pilot to apply immediate corrective or recovery controls thus enabling him to maintain position. This is in contrast to flights without the AAA/SWS when stall AOA was exceeded and aircraft behavior did not reveal the fact until AOA was well above stall and position was lost due to excessive recovery time. 3. Solid FM tone also reminds pilot that he must fly so as to conserve position when he is at a performance disadvantage.
Miscellaneous	1. When engaged in ACM with an aircraft that has a performance advantage, especially in roll, AOA information was never acquired from the visual display, the time required was prohibitive. 2. Should be able to easily train a pilot to use the AAA/SWS and effectively use its information in actual ACM.

Subject	Pilot Comments
	3. Two-way voice communication did not seem to affect ability to use the AAA/SWS.
	4. In sustained usage found that did not consciously "listen" for the AAA/SWS but still utilized it, especially with respect to α_3 and stall AOA.

Table XI. Pilot Comments from ACM Simulation Testing Program.

Subject	Pilot Comments
Effects of "noise" on AAA/SWS reception and perception.	1. Volume level needed to be higher in the presence of cockpit ambient noises. (Volume level on prototype used for this phase of testing had a fixed maximum level. An audio amplifier will correct this). 2. Transducer noise inputs to the AAA/SWS were not reflected in its output, i.e. the signal was clear and undistorted throughout its range of operation. 3. Sustained "g" loadings had no effect on the AAA/SWS output.
Utility of the AAA/SWS in take-off and landing phases of flight.	1. Enables pilot to go directly to AOA required for desired performance on lift-off from take-off roll and to maintain it during climb-out. 2. Allows the pilot to devote entire visual attention to attitude and altitude control in landing phase and thus fly more precisely to a desired landing spot. Should be useful in V/STOL. 3. Two-way voice communication during landing did not preclude the use of the AAA/SWS and the AAA/SWS output did not mask this type of Comm.

Table XII. Pilot Comments From Aircraft Testing Program.

V. CONCLUSIONS AND DISCUSSION

Careful examination of the results for each phase of testing led to the following conclusions.

A. EFFECTS ON PERFORMANCE AND CONFIDENCE LEVEL

Accurate knowledge of aircraft angle of attack in the large angle of attack region markedly improves pilot performance and confidence level, and the AAA/SWS format does present angle of attack information in a meaningful fashion. Moreover, the AAA/SWS is superior to both "seat of the pants" and the present visual methods of display of this information, particularly when the environment is dynamic and the visual task loading high, and when the performance of the aircraft being tracked exceeds that of the attacker for an extended period of time. These conclusions are borne out in both the laboratory testing and ACM simulation testing and are nowhere more clearly illustrated than in the representations of percent successes for the tail-chase shown in Figures 10a - 10d, and in the angle of attack time histories shown in Figures 13 and 14. In addition, both the pilot comments as listed in Table XI and the RMS rate error averages for target tracks 3 and 4, shown in Figures 9c and 9d respectively, support these conclusions.

Positive identification of the region preceding stall and of stall angle of attack can both affect the strategy employed by the pilot in tracking and reduce the incidences of

departure in ACM. The AAA/SWS accomplishes these requirements in a manner which exceeds presently used methods. These conclusions were again drawn from the results of the laboratory and ACM simulation testing. In the former tests, percent successes as shown in Figures 10a - 10d and the average penetration times shown in Figures 11a - 11d all testify to the relative ability of the various displays to enable the pilot to accomplish these objectives. In the latter tests, evidence in support of these conclusions is obtained from pilot comments as given in Table XI and is verified in time histories for the elevator. As shown in Figures 14a and 14b, a measure of the time required to recognize that stall angle of attack had been exceeded can be made by noting when the primary departure recovery technique, control stick forward, was applied.

B. USE IN TAKE-OFF AND LANDING

It can be concluded from pilot comments such as those shown in Table XII that the AAA/SWS does appear to be useful in take-off and landing but further testing is definitely warranted to measure this utility.

C. FUNCTION OF THE ELECTRONICS PACKAGE

The AAA/SWS functioned properly in the limited aircraft testing performed but more extensive testing is recommended to furnish reliability data.

APPENDIX A

A Detailed Analysis of the AAA/SWS Electronics Package

A. INTRODUCTION

With the exception of the device used to generate the saw-tooth waveform (the EXAR XR-320 Timing Circuit) contained in the Angle of Attack Detection Section and the VCO and switching circuit (the EXAR XR-205 Waveform Generator) used in the Output Section, the AAA/SWS electronic components consisted chiefly of precision operational amplifiers (op-amps), high-speed comparators and their associated resistors, potentiometers and diodes. Consequently it was found that a more convenient method of analysis than by functional sections as those shown in Fig. 7a was by component blocks like those shown in Fig. 15. A build-up method of analysis was carried out by deriving models and transfer functions for the various basic components, i.e. op-amps, comparators and potentiometers and progressively combining them until an overall transfer function for the entire AAA/SWS was obtained.

The general op-amp model utilized for this analysis is shown in Fig. 16a. Reduction of this model to the two functionally required, i.e. inverter and non-inverter, was accomplished by shorting pins 1 and 2 in the former case and pins 1 and 3 in the latter. These are shown in Figs. 16b and 16c along with the two-port parametric representations utilized for analysis, i.e. the inverse hybrid parameters.

The simplified parameters also shown were found by substituting the specified values for the op-amps actually employed (Fairchild μA 741)

$$Z_n = 10^6\Omega \qquad Z_o = 50\Omega \qquad A = 10^4$$

and specifying that

$$0 \leq R_o \leq 10^6\Omega \qquad 0 \leq R_1 \leq 10^6\Omega \qquad 0 \leq R_g \leq 10^6\Omega$$

The model utilized for the high-speed comparators actually employed (Fairchild μA 710) are shown in Fig. 17.

The input-output relationships for each block were derived as shown in Figs. 18a-18d and the relationships and interactions of each of the blocks are shown in Fig. 19.

B. ANALYSIS

1. Block 1.

Given: $V_{A2} \leq 0$

$$V_{2B} = (R_o/R_1)_B \left[(R_o/R_1)_A V_{A1} + (R_o/R_2)_A V_{A2}\right] - (R_o/R_1)_B Z_{oA} I_{2A}$$

Note: Since $(R_o/R_1)_B = 1.0$, $Z_{oA_{max}} = 50$, $I_{2A} = 1.0$

then the last term is on the order of .05 volts and it was neglected. Since $(R_o/R_1)_B \geq 0$ the sign of V_{2B} is determined by bracketed term. $V_{2B} \geq 0$ $\qquad |V_{A1}| \geq (R_1/R_2)_A |V_{A2}|$

$\therefore$

2. Comparators ①, ③, ④.

Given: $V_{①2} \geq 0$, $V_{③2} \geq 0$, $V_{④2} \geq 0$

from previous analysis of Block 1, $V_{2B} \geq 0$

for ① : $V_{2①} = \begin{cases} 3.0, & V_{2B} \geq V_{①2} \\ -.5, & V_{2B} < V_{①2} \end{cases}$

for ③ : $V_{2③} = \begin{cases} 3.0, & V_{2B} \geq V_{③2} \\ -.5, & V_{2B} < V_{③2} \end{cases}$

for ④ : $V_{2④} = \begin{cases} 3.0, & V_{2B} \geq V_{④2} \\ -.5, & V_{2B} < V_{④2} \end{cases}$

3. Block 2

Given: $1.1 \leq V_{1E} \leq 4.0$ $\qquad V_{F2} \leq 0$

Required that $V_{2F} \geq 0$

$$V_{2F} = -\left[(R_o/R_1)_F V_{1E} + (R_o/R_2)_F V_{F2}\right] + Z_{oF} I_{2F}$$

Note: Neglect last term for similar reason to that in block 1.

So $\quad V_{2F} = -(R_o/R_1)_F V_{1E} + (R_o/R_2)_F V_{F2} \geq 0$

$$(R_o/R_1)_F V_{1E} + (R_o/R_2)_F V_{F2} \leq 0$$

$\therefore \quad V_{2F} \geq 0 \qquad\qquad \left|V_{F2}\right| \geq (R_2/R_1)_F \left|V_{1E}\right|$

for the maximum case $V_{1E} = 4.0$

So $\qquad\qquad \left|V_{F2}\right| \geq (R_2/R_1)_F (4.0)$

For this circuit it is required that $V_{F2max} = 6.0$ so $(R_2/R_1)_F \leq 1.5$

4. Comparator 2

Given: $V_{2B} \geq 0 \quad V_{2F} \geq 0$

$$V_{2②} = \begin{cases} 3.0, & V_{2B} \geq V_{2F} \\ -.5, & V_{2B} < V_{2F} \end{cases}$$

5. Potentiometers

$V_{2K_1} = K_1 V_{2B}$ $\quad$ where $\quad 0 \leq K_1 \leq 1.$

$V_{2K_2} = K_2 V_{2\,1}$ $\quad$ where $\quad 0 \leq K_2 \leq 1.$

6. Block 3

Given: $V_{C1} = K_2 V_{2③}$ $\qquad V_{C2} = K_1 V_{2B}$ $\qquad V_{C3} \leq 0$

$$V_{2C} = -\left[(R_o/R_1)_C V_{C1} + (R_o/R_2)_C V_{C2} + (R_o/R_3)_{C3}\right] + Z_{oC} I_{2C}$$

Note: Neglect last term as before

$$\therefore \quad V_{2C} = -\left[(R_o/R_1)_C K_2 V_2 \text{①} + (R_o/R_2)_C K_1 V_{2B} + (R_o/R_3)_C V_{C3}\right]$$

V_2 ①	V_{2B}	V_{C3}	V_{2C}
-.5	0	0	$0.5(R_o/R_1)K_1 = A$
-.5	0	-V	$A + (R_o/R_3)V = B$
-.5	V_{2B}	0	$A - (R_o/R_2)K_1V_{2B}$
-.5	V_{2B}	-V	$B - (R_o/R_2)K_1V_{2B}$
3.0	0	0	$-3.0(R_o/R_1)K_2 = C$
3.0	0	-V	$C + (R_o/R_3)V = D$
3.0	V_{2B}	0	$C - (R_o/R_2)K_1V_{2B}$
3.0	V_{2B}	-V	$D - (R_o/R_2)K_1V_{2B}$

7. Block 4

Given: $V_{D1} = V_2$ ③ $\qquad V_{D2} = V_2$ ④ $\qquad V_{D3} = V_2$ ②

$$V_{2D} = (R_o/R_1)_D\left\{(R_G/R_{eq})_D\left[R_{2D}V_{D3} + R_{3D}V_{D2}\right] - V_{D1}\right\} + (R_G/R_{eq})_D\left[R_{2D}V_{D3} + R_{3D}V_{D2}\right]$$

or $\quad V_{2D} = R_{R1}V_2 \text{②} + R_{R2}V_2 \text{④} - R_{R3}V_2 \text{③}$

where $\quad R_{R1} = \left[(R_o + R_1)/R_1\right]_D R_{GD}\left[R_3/R_{eq}\right]_D \qquad R_{R3} = R_o/R_1$

$\qquad\quad R_{R2} = \left[(R_o + R_1)/R_1\right]_D R_{GD}\left[R_2/R_{eq}\right]_D$

V_2 ③	V_2 ④	V_2 ②	V_{2D}
-.5	-.5	-.5	$-.5\ R_{R1} - .5\ R_{R2} + .5\ R_{R3}$
-.5	-.5	3.0	$-.5\ R_{R1} - .5\ R_{R2} - 3.0\ R_{R3}$
-.5	3.0	-.5	$-.5\ R_{R1} + 3.0\ R_{R2} + .5\ R_{R3}$
-.5	3.0	3.0	$-.5\ R_{R1} + 3.0\ R_{R2} - 3.0\ R_{R3}$
3.0	-.5	-.5	$3.0\ R_{R1} - .5\ R_{R2} + .5\ R_{R3}$
3.0	-.5	3.0	$3.0\ R_{R1} - .5\ R_{R2} - 3.0\ R_{R3}$
3.0	3.0	-.5	$3.0\ R_{R1} + 3.0\ R_{R2} + .5\ R_{R3}$
3.0	3.0	3.0	$3.0\ R_{R1} + 3.0\ R_{R2} - 3.0\ R_{R3}$

C. AN EXAMPLE

1. Particular Specifications to be Satisfied

AOA	V_{A1}*	Freq.	V_{2C}	Output	V_{2D}
-26.0	-7.0	0			
0.0	0.0	0	?	Off	$\leq$ 0.0
14.9	4.0	0			
15.0	4.0	500 Hz	-0.80	FM	2.0
20.9	5.6	linear	-1.22	tone	
21.0	5.6	incr.	-1.22	FM/PWM	2.0
25.9	7.0	with	-1.63	tone	0.0
26.0	7.0	AOA	-1.63	FM	$\geq$2.0
33.9	9.1	1500 Hz	-3.60	tone	
34.0	9.1	2200 Hz Incr.	-5.10		
45.0	12.0	@ AOA	-5.93		

* V_{A1} is an angle of attack transducer output

2. AAA/SWS Component Outputs

The outputs required for the various component parts of the AAA/SWS for the specifications listed are shown in Tables XIIIa and XIIIb. In addition the required values for Block 2 components and resistor sizes chosen are shown in Figs. 20 and 21 respectively.

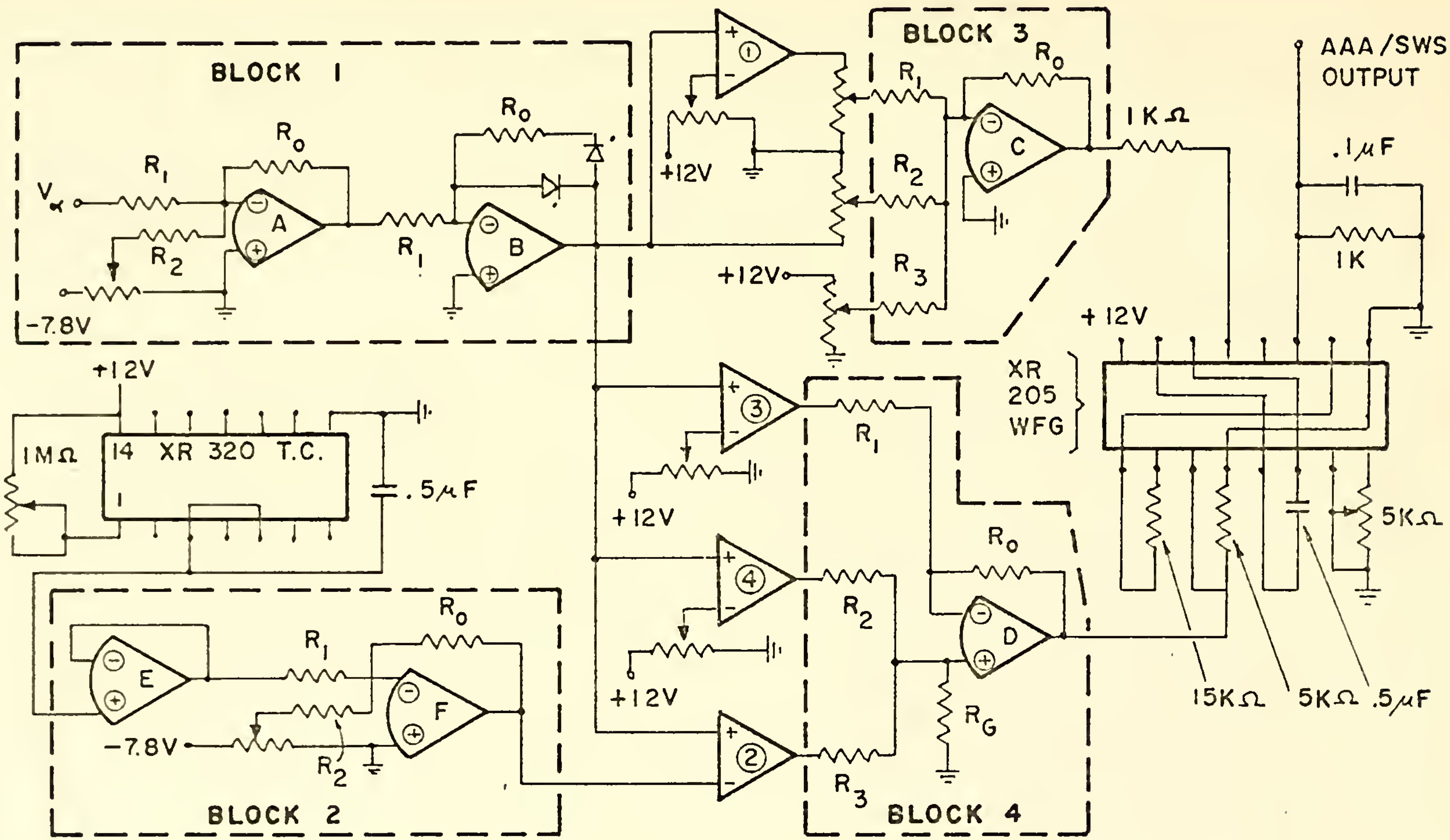


Figure 15. Component Circuit Diagram of AAA/SWS Electronic Package

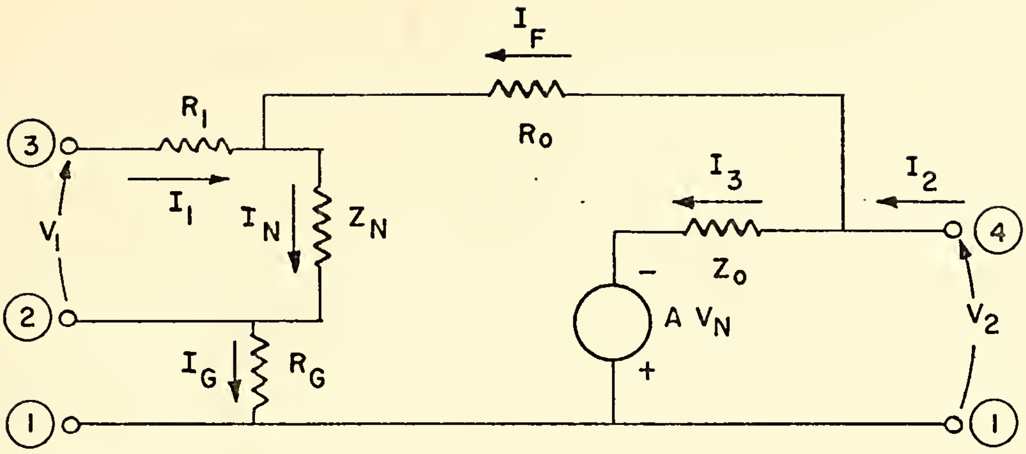
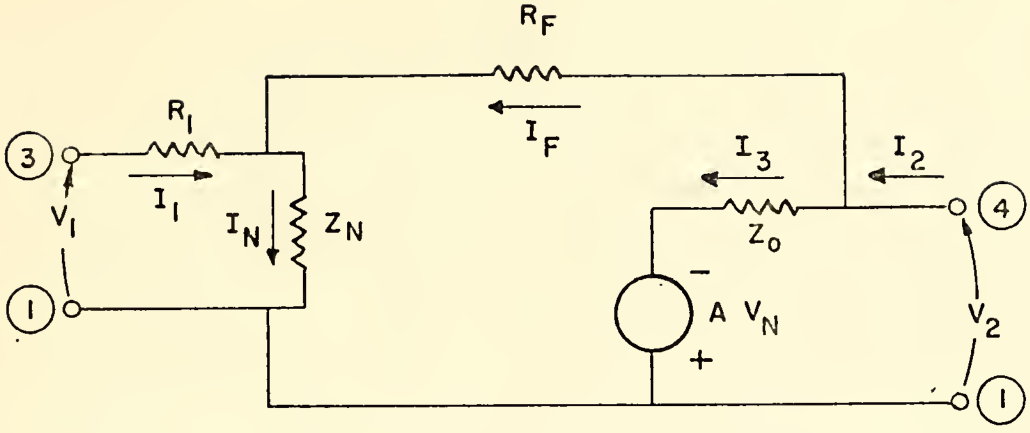


Figure 16a. The General Operational Amplifier Model



$$g_{11} = \frac{Z_N(1 + A) + R_0 + Z_0}{R_1\left[(1 + A)Z_N + R_0 + Z_0\right] + Z_N(R_0 + Z_0)}$$

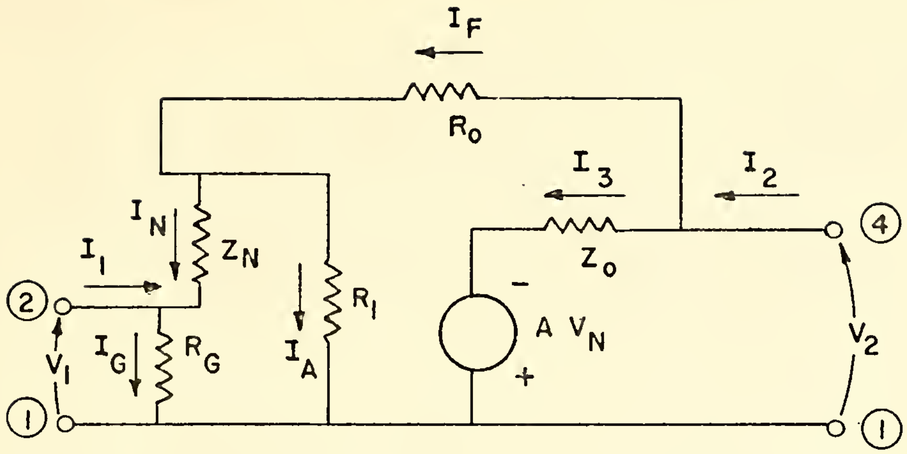
$$g_{12} = \frac{-Z_N Z_0}{Z_N\left[(1 + A)R_1 + R_0 + Z_0\right] + R_1(R_0 + Z_0)}$$

$$g_{21} = \frac{Z_N Z_0 - A Z_N R_0}{R_1\left[(1 + A)Z_N + R_0 + Z_0\right] + Z_N(R_0 + Z_0)}$$

$$g_{22} = \frac{Z_0\left[Z_N(R_0 + R_1) + R_1 R_0\right]}{Z_N\left[(1 + A)R_1 + R_0 + Z_0\right] + R_1(R_0 + Z_0)}$$

$$g_{11} = \frac{1}{R_1} \qquad g_{12} = 0 \qquad g_{21} = -\frac{R_0}{R_1} \qquad g_{22} = 0$$

Figure 16b. The Inverter Op-Amp Model with General and Simplified Inverse Hybrid Parameters Shown.



$$g_{11} = \frac{(AR_1 + R_0)\, Z_N + R_G\,(R_1 + R_0) + R_1\, R_0}{R_G\,[AR_1 + R_0]\, Z_W + R_1\, R_0\, R_G}$$

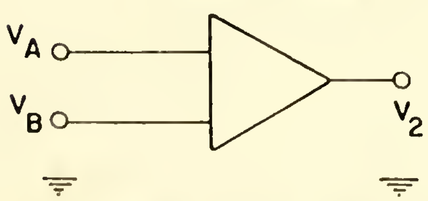
$$g_{12} = \frac{-\,R_1\, Z_0}{(R_1 + Z_N)\, Z_0 + AR_1\, Z_N + R_1\, R_0}$$

$$g_{21} = \frac{A\, Z_N\,(R_0 + R_1)}{(A\, R_1 + R_0)\;\; Z_N + R_1\;\, R_0}$$

$$g_{22} = Z_0 \left[\frac{Z_N\,(R_1 + R_0) + R_1\, R_0}{(R_1 + Z_N)\;\; Z_0 + AR_1\, Z_N + R_1\, R_0} \right]$$

$$g_{11} = \frac{1}{R_G} \qquad g_{12} = 0 \qquad g_{21} = \frac{R_0 + R_1}{R_1} \qquad g_{22} = \frac{1}{A}$$

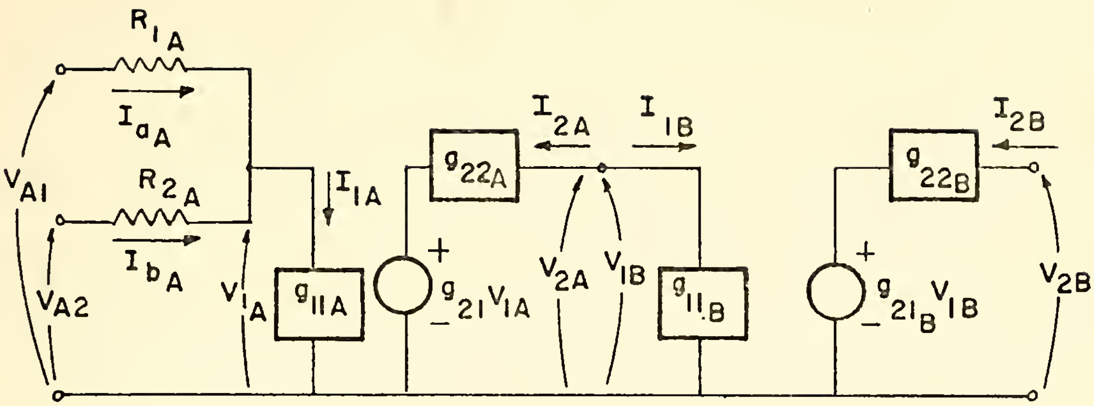
Figure 16c. The Non-Inverter Op-Amp Model with General and Simplified Inverse Hybrid Parameters Shown.



$V_2 = -0.5;\ V_A + V_B < 0$

$V_2 = 3.0;\ V_A + V_B \geq 0$

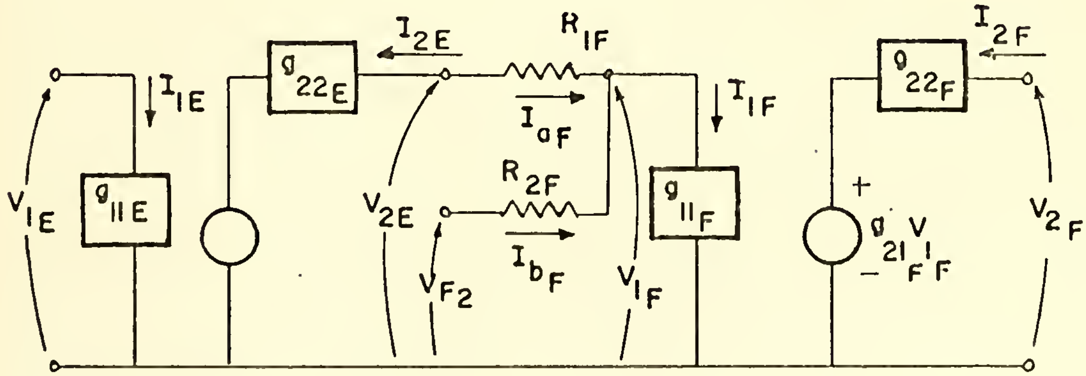
Figure 17. Model Used for High-Speed Comparator



$$V_{2B} = \left(\frac{R_0}{R_1}\right)_B \left[\left(\frac{R_0}{R_1}\right)_A V_{A1} + \left(\frac{R_0}{R_2}\right)_A V_{A2}\right] - \left(\frac{R_0}{R_1}\right)_B Z_{0_A} I_{2_A}$$

$$I_{1_{A\,MAX}} = \frac{V_{A1}}{R_{1A}} + \frac{V_{A2}}{R_{2A}}$$

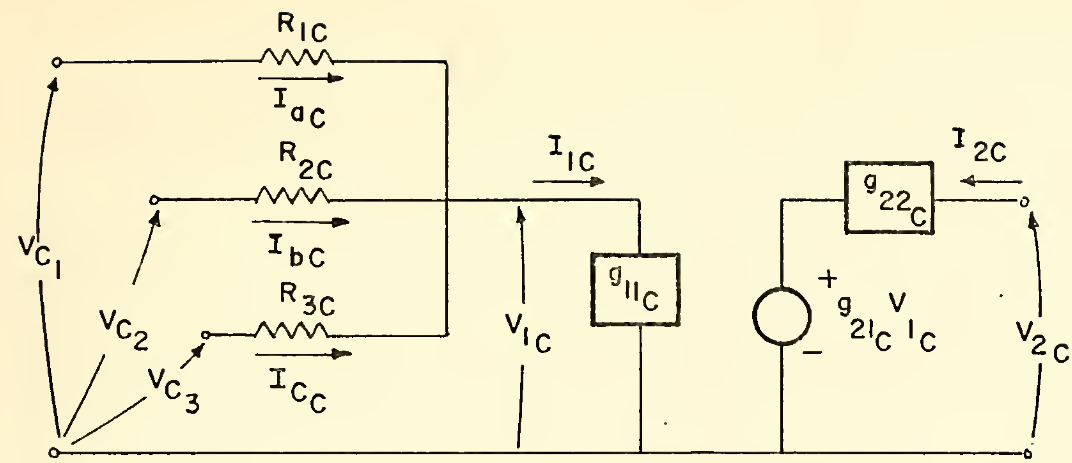
Figure 18a. Input-Output Relationships for Block 1



$$V_{2_F} = -\left[\left(\frac{R_0}{R_1}\right)_F V_{1E} + \left(\frac{R_0}{R_2}\right)_F V_{F2}\right] + Z_{0_F} I_{2_F}$$

$$I_{1_{E\,MAX}} = V_{1_E} G_{11_E} = 0$$

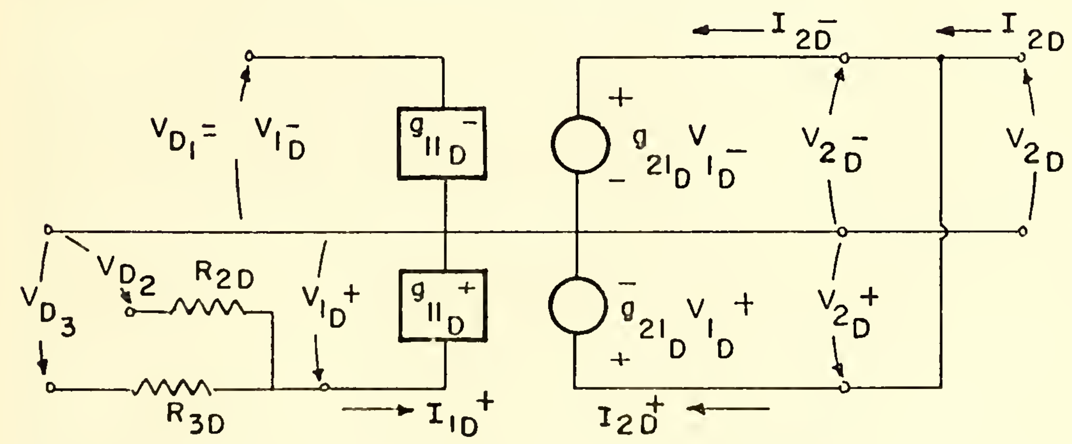
Figure 18b. Input-Output Relationships for Block 2



$$V_{2C} = -\left[\left(\frac{R_0}{R_1}\right)_C V_{C1} + \left(\frac{R_0}{R_2}\right)_C V_{C22} + \left(\frac{R_0}{R_3}\right) V_{C3}\right] + Z_{0_C}\, I_{2C}$$

$$I_{1C\,MAX} = \frac{V_{C1}}{R_{1C}} + \frac{V_{C2}}{R_{2C}} + \frac{V_{C3}}{R_{3C}}$$

Figure 18c. Input-Output Relationships for Block 3



$$V_{2_D} = \left(\frac{R_0}{R_1}\right)_D \left\{\left(\frac{R_G}{Reg}\right)_0 \left[R_{2_D} V_{D_3} + R_{3_D} V_{D_2}\right] - V_{D_1}\right\}$$

$$+ \left(\frac{R_G}{Reg}\right)_D \left[R_{2_D} V_{D_3} + R_{3_D} V_{D_2}\right]$$

where: $Reg = R_2\, R_{G_D} + R_{3_D}\, R_{G_D} + R_{2_D}\, R_{3_D}$

$$I_{1D\,MAX} = \frac{V_{D_1}}{g_{11_D}} + \frac{V_{D_2}}{R_{2_D}} \quad \frac{V_{D_3}}{R_{3_D}}$$

Figure 18d. Input-Output Relationships for Block 4

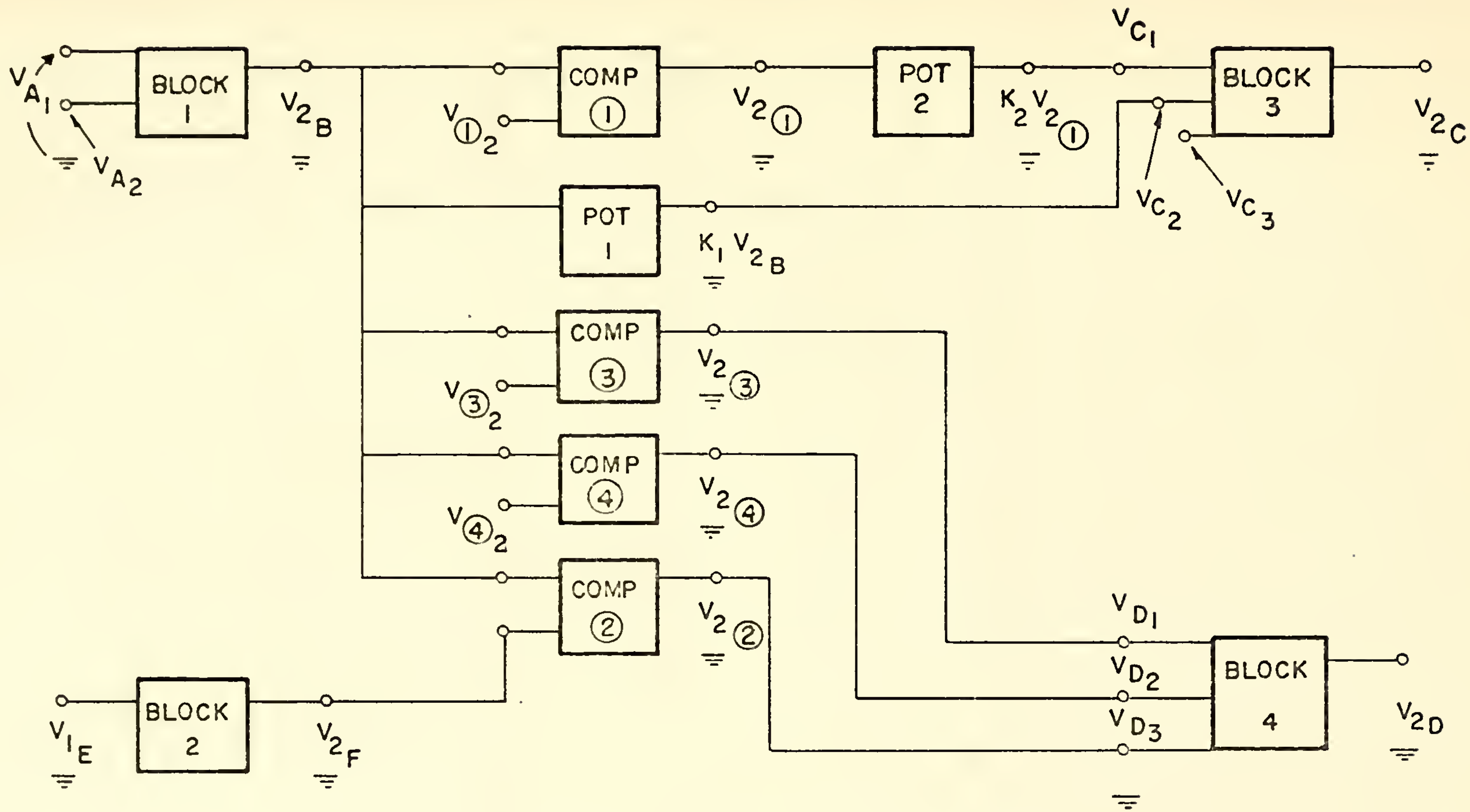


Figure 19. Relationships and Interactions of Each of the Blocks

Block 2

Time	$V_{1E}=V_{F1}$	V_{F2}	V_{2F}
0.0	1.10	−4.73	3.0
0.3	5.0	↓	1.6
0.3^+	1.1	↓	3.0
0.6	5.0	↓	1.6

Where: $V_{2F} = -(R_0/R_1)_F\left[V_{F1} + (R_1/R_2)_F\, V_{F2}\right]$

and choosing $(R_1/R_2)_F = 2.0$

$$V_{F2} = \frac{V_{F1}(t = 0.0)\ 1.6 - V_{F1}\ (t = 0.3)\ 3.0}{2.0\ (3.0 - 1.6)}$$

$$V_{F2} = -4.73 \text{ V}$$

In addition: $(R_0/R_1)_F = \dfrac{-3.0}{V_{F1}\ (t = 0.0) + 2.0\ V_{F2}}$

$$(R_0/R_1)_F = 0.359$$

Choosing $R_1 = 20\ \text{K}\Omega$, then $R_2 = 10\ \text{K}\Omega$ and $R_0 = 7.18\ \text{K}\Omega$

Figure 20. Required Component Values for Block 2

	A	B	F	C	D
R_o	20 K	20 K	7.18 K	20 K	20 K
R_1	20 K	20 K	20 K	20 K	20 K
R_2	20 K	----	10 K	20 K	20 K
R_3	----	----	----	20 K	20 K
R_G	----	----	----	----	1 MG

Figure 21. Resistor Values Chosen (Ohms)

AOA	V_{A1}	V_{A2}	V_{2B}	V_1 ②	V_2 ①	V_{F2}	V_2 ②	$V_{③2}$	V_2 ③	$V_{①2}$	V_2 ④
-26.0	-7.0	-4.0	0.0	5.1	-0.5	3.0	-0.5	1.6	-0.5	0.05	-0.5
0.0	0.0		0.0			1.6					
14.9	4.0		0.0								
15.0	4.0		0.0								3.0
20.9	5.6		1.6								
21.0	5.6		1.6				3.0		3.0		
25.9	7.0		3.0				-0.5				
26.0	7.0		3.0				3.0				
33.9	9.1		5.1								
34.0	9.1		5.1		3.0						
45.0	12.0		6.0*								

Table XIIIa. AAA/SWS Component Outputs.

* Amplifier saturation

AOA	$.44V_2$ ①	$.55V_{2B}$	V_{C3}	V_{2C}	V_2 ③	V_2 ④	V_2 ②	V_{2D}
-26.0	-.22	0.0	1.02	-0.8	-0.5	-0.5	-0.5	-0.5
0.0		0.0						
14.9		0.0						
15.0		0.0				3.0		3.0
20.9		0.88		-1.22				
21.0		0.88		-1.22	3.0		3.0	3.0
25.9		1.66		-1.63			-0.5	-0.5
26.0		1.66		-1.63			3.0	3.0
33.9		2.80		-3.60				
34.0	1.32	2.80		-5.10				
45.0		3.30		-5.64				

Table XIIIb. AAA/SWS Component Outputs

* Amplifier saturation

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13. ABSTRACT

Maximum performance and stall avoidance can only be realized in high-performance aircraft if the pilot is fully aware of angle of attack. Because present methods of providing this information have proven to be inadequate, an alternative method has been proposed. This paper describes the Aural Angle of Attack/Stall Warning System, an electronic device which produces a coded aural display meeting the requirements of 1) providing angle of attack information in the large angle of attack region, 2) providing positive warning of approach to and passage through stall angle of attack and 3) accomplishing these without distracting from the primary visual task. Evaluations were conducted utilizing a simulated tail-chase tracking task, a full-scale

air combat manoeuvering simulation and actual aircraft testing. Results indicated that 1) there was marked improvement in pilot performance in the air combat manoeuvering environment with the addition of an aural system, 2) the electronic package could operate efficiently in an actual aircraft and 3) the aural system has a definite utility in the take-off and landing phases of flight.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Aircraft						
Angle of Attack						
Aural						
Departure						
Stall						
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Warning						
Display						
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